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One of the methods for on-site disposal of wastewater from individual homes is by evaporation. Two types of evaporative disposal systems have been investigated in this study; evapo-transpiration beds and mechanical evaporation units.

Twenty nine test lysimeters of 0.22 cubic meters volume each were utilized to evaluate the effect of design and operational parameters for ET beds. The variables studies were wastewater loading rate, effect of the weather variables of evaporation and rainfall, ET sand size, evaporation rate as a function of the water saturation depth, and the transpiration contribution of surface vegetation. A design method is presented along with cost data and an analysis of the national application potential of this type of system.

The evaporation of wastewater using mechanical systems was studied using a pilot scale unit, constructed as part of the project. Two types of evaporation designs were evaluated. Design equations were established for both units. Cost data and analysis of national application potential is also presented.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

In the role of developing alternative wastewater technologies for use in rural communities, freedom from the limitations of soils has long been sought in order to permit the optimum development of the Nation's land resources. One such non-dependent solution which has been employed for individual households in recent years is the evaporation-transpiration disposal of wastewater. This report details the results of a scientific investigation of the relevant parameters affecting the performance of evaporation and evapotranspiration systems for non-sewered rural communities. It serves as a basis upon which the feasibility of these types of alternative systems can be determined.

Francis T. Mayo
Director
Municipal Environmental
Research Laboratory

ABSTRACT

One of the methods for on-site disposal of wastewater from individual homes is by evaporation. Two types of evaporative disposal systems have been investigated in this study; evapotranspiration beds and mechanical evaporation units.

Evapotranspiration beds can be designed for completely evaporative disposal with no discharge to the adjacent soil or as combination beds utilizing seepage as well as evaporation disposal. The non-discharging type of ET bed was investigated in this study but the results can also be interpreted to describe the evaporative portion of the combination, ET seepage bed. Twenty nine test lysimeters of 0.22 cubic meters volume each were utilized to evaluate the effect of design and operational parameters for ET beds. The variables studies were wastewater loading rate, effect of the weather variables of evaporation and rainfall, ET sand size, evaporation rate as a function of the water saturation depth, and the transpiration contribution of surface vegetation. A design method is presented along with cost data and an analysis of the national application potential of this type of system.

The evaporation of wastewater using mechanical systems was studied using a pilot scale unit, constructed as part of the project. Two types of evaporation designs were evaluated. One unit utilized a row of circular, vertically mounted disks, rotated about a horizontal shaft with a portion of the disk submerged in wastewater in reservoirs. The wetted area of the disks exposed to the atmosphere provided the evaporation surface. The second unit was similar, except that a cylinder was made up of concentric wraps of burlap cloth as the evaporation surface. The burlap became wetted as the partially submerged cylinder turned in the vat of wastewater. Ambient air was forced through the center shaft and moved through the wetted wraps producing evaporation of the wastewater. The variables studied for the two units were: the wastewater loading rate, ambient air evaporation potential, wind speed, amount of submergence and disk spacing. Design equations were established for both units. Cost data and analysis of national application potential is also presented.

This report is submitted in fulfillment of Contract Number R 803871-01-0 by the University of Colorado under the sponsorship of the U.S. Environmental Protection Agency. The report covers a period of July 1, 1975 through April 30, 1978 and work was completed on May 31, 1978.

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LIST OF SYMBOLS

A -- interfacial area of evaporation
A_s -- exposed wetted surfae area of CCE
A_{vp} -- Vertical projected area of the set of disks of the RDE
A_{ws} -- wetted surface area of the RDE
BHP -- horse power required
C -- ratio of cloudless hours to total sunshine hours available
C_s -- heat of the entering air
Evap -- evaporation rate
G -- heat from the ground
G_g -- mass velocity of the unsaturated air per unit area of wetted surface
H -- humidity of air
Ha -- humidity of ambient air
Hi -- humidity of entering air
Ho -- humidity of exiting air
Hv -- heat of vaporization
Hw -- humidity of wet bulb temperature
ΔH_1 -- humidity deficit of ambient air with respect to saturation
ΔH_2 -- humidity deficit of piped air with respect to saturation in CCE
K -- von Karman constant
Kg -- mass transfer coefficient
K' -- constant
Ma -- molecular weight of air
Mv -- molecular weight of water vapor
P -- atmospheric pressure
Q -- volumetric flow rate of air
R -- gas constant
R_s -- sunlight radiation
T -- temperature
Ta -- air temperature
Tmxd -- reservoir liquid temperature, concentric cylinder and rotating disk evaporator
T_s -- air temperature at adiabatic saturation
T_{ss1} -- adiabatic saturation temperature of piped air in CCE
Tw -- temperature of wet bulb
W -- wind speed
Wa -- air flow rate
Ww -- mass of water vaporized with time

LIST OF SYMBOLS

a and b -- empirical constants
b_1 -- compressed air mass transport coefficient
b_2 -- coefficient for effectiveness of capture of solar radiation
e_a -- vapor pressure of ambient air
e_f -- efficiency fraction of a compressor
e_o -- vapor pressure at air saturation
e_w -- vapor pressure at wet bulb temperature
f -- cloudiness factor
hg -- heat transfer film coefficient
k_1 -- ambient air mass transport coefficient
m -- emissivity
n -- compression constant for air
q -- rate of heat flow
r -- reflectance coefficient
w -- mass rate of evaporation
z -- elevation above ground of wind speed measurement
z_o -- roughness length

γ --psychrometric constant
Δ --slope of the saturated vapor pressure-temperature curve
ε --energy
ε_{ST} --total short wave solar radiation reaching an evaporation surface
ε_{vap} --energy utilized in water evaporation
$\varepsilon_{reflect}$ --reflected solar radiation
$\varepsilon_{longwave}$ --net longwave radiation exchange between atmosphere and wetted surface
$\varepsilon_{boundary}$ --energy lost or gained from the earth
$\varepsilon_{internal}$ --energy stored or lost by the materials of the evaporation system
$\varepsilon_{temperature\ loss}$ --sensible heat loss to the atmosphere
$\Delta\varepsilon_{advected}$ --energy brought in by water entering the system
ε_R --total potential solar radiation reaching the earth
λ_s --latent heat of vaporization at saturation humidity
λ_{TW} --latent heat of vaporization
σ --Stefan-Boltzman coefficient at wet-bulb temperature
ρ --density of air

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SECTION 1

INTRODUCTION

A significant number of individual homes in the United States are not connected to any form of central sanitary sewerage and utilize individual home, on-site systems for wastewater disposal. Based on information from the 1970 census, approximately twenty-nine percent of the nation, or over fifty million people, utilize this type of wastewater control for their residences. This is an important consideration for health authorities since the number of people served by on-site systems is greater than the total people living in all cities of greater than 100,000 population.

On-site disposal consists primarily of the use of a septic tank and a soil absorption system, which is commonly termed a leaching field. Approximately one-fourth of the homes in the United States utilize this system. The remaining four percent of dwelling units, housing about nine million persons, utilize other methods such as aerobic treatment, evaporation disposal, sand filters and the more primitive forms such as cesspools and privies.

The septic tank-soil absorption system (ST-SAS) usually provides the most economic alternative for individual home disposal where conditions favorable for leaching fields exist. Wenk (1971) has shown that geological limitations for the use of leaching fields exist in a portion of every state in the nation. The limitations result from the following geologic conditions: very shallow soil mantle, high groundwater tables, tight soils or fractured rock which will not permit adequate filtration purification of the wastewater before reaching the groundwater reservoir. Failure of ST-SAS systems is often observed as chemical or bacterial pollution of groundwaters. In most cases, it is indicated by appearance of effluents at the ground surface.

The proper application of individual systems for new homes is generally controlled by local health authorities. Where the use of ST-SAS is proposed, a soil percolation test and geologic survey are used to establish suitability. If any of the limitations preclude the use of ST-SAS, a specially designed system must be used. Such methods include evapo-transpiration disposal (ST-ET), import fill, mounded disposal units, intermittent sand filters, or special mechanical treatment providing a high degree of wastewater purification.

The evapo-transpiration (ST-ET) method is unique in that it can be utilized in such a way as to be non-discharging to the surface water or groundwater reservoir. This precludes the potential pollution of drinking water sources. Most of the specially designed systems involve a higher construction cost than ST-SAS. Under the proper circumstances the ST-ET method may be the most economical of the specially designed systems.

Evaporative methods may be used in several different ways. Sealed evaporation-transpiration beds composed of water tight liners and specifically selected sands are presently in use. A somewhat similar appearing unit uses an unsealed bed which has evaporation-transpiration as the chief disposal mechanism but percolation is also utilized. The use of mechanical evaporative devices for wastewater is in the development stage. Evaporative mechanical systems can be designed to require only a very small amount of electrical energy and have a very low maintenance requirement, two desirable features of any individual home wastewater disposal concept.

This study was initiated to investigate the application of the evaporation disposal concept under the condition that no water is discharged to surface streams or groundwater. Two general types of units have been evaluated at laboratory scale, evaporation-transpiration beds and mechanical evaporation systems.

A typical ET bed installation is shown in Figure 1. Septic tank effluent flows into the lower portion of the bed as it is generated. The water is raised to the top portion of the bed by capillary action in the fine sand. Evaporation takes place at or near the surface of the bed. Plant life may be used to raise the water from the area of the root zone to the leaves to be removed by transpiration.

In this study, twenty-nine small scale ET bed lysimeters were used to provide concurrent evaluation of several design and operational parameters. This permitted the study of parametric variations under the same ambient conditions. A drawing of the lysimeter unit is shown in Figure 2.

Two types of mechanical evaporation units were studied (see Figures 3 and 4). A rotating disk mechanical evaporation unit is shown in Figure 3. The disks turn slowly and the moisture on the wetted surface is continuously transferred to the ambient air moving over the unit. The concentric cylinder mechanical evaporation unit of Figure 4 utilizes forced air entering at the center of the cylinder and moving outward

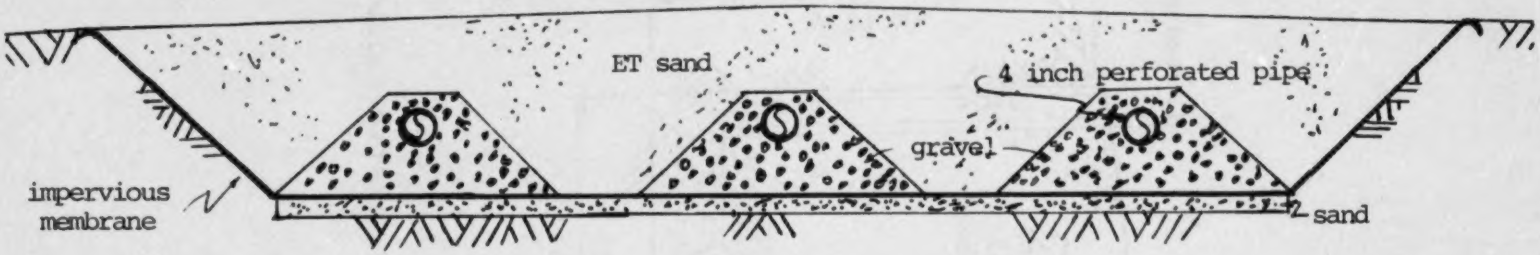

ET sand
4 inch perforated pipe
gravel
impervious membrane
sand

Figure 1. Typical ET bed cross-section.

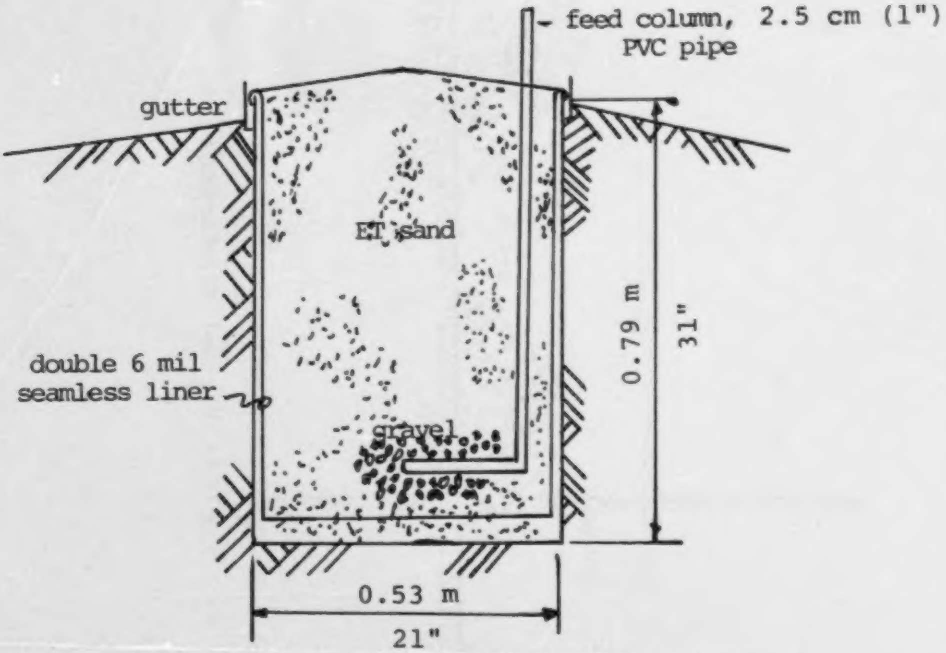

feed column, 2.5 cm (1")
PVC pipe
gutter
ET sand
double 6 mil
seamless liner
gravel
0.79 m
31"
0.53 m
21"

Figure 2. Lysimeter cross-section.

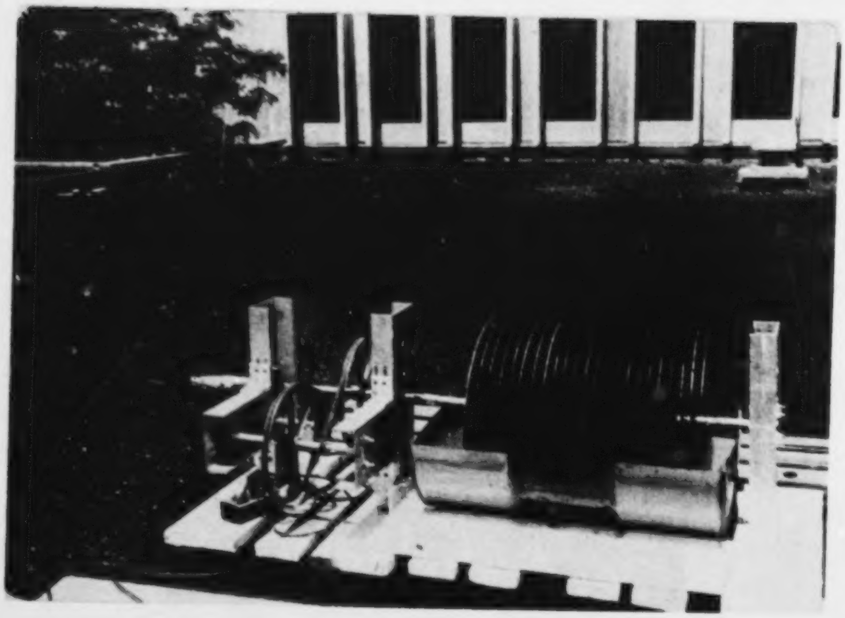


Figure 3. Rotating disk test unit

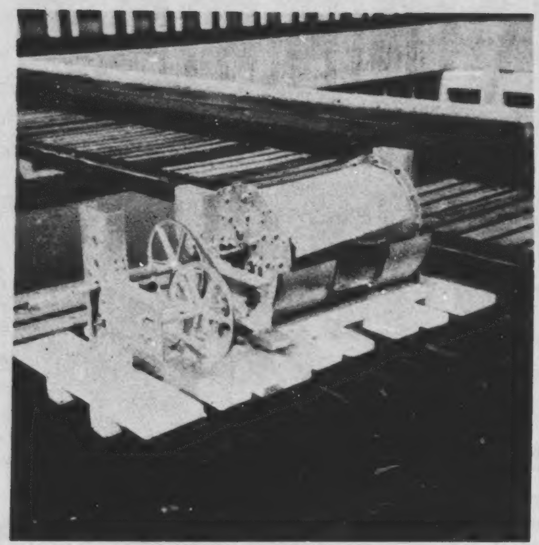


Figure 4. Concentric cylinder test unit.

through the wetted cloth wraps for vapor transport. Both mechanical units require a septic tank for pretreatment and a storage vault as a part of the total disposal system. Each of the test units shown was capable of evaporating about twenty-five liters per day (6-7 gal/day) under average conditions.

The purpose of the study was the evaluation of design and operational parameters for each type of unit, correlation of laboratory data with field units for ET beds and the development of cost criteria for the full scale installation of both types of units.

SECTION 2

CONCLUSIONS

Nearly twenty million homes in the U.S., housing approximately twenty-nine percent of the population, are in unsewered areas and utilize individual home treatment and disposal techniques for wastewater discharge. The septic tank and soil absorption system is the most common individual home wastewater disposal method because of the generally lower cost involved. Many areas of the U.S. are not suited for soil absorption systems and alternate methods must be used.

Disposal methods utilizing evaporation processes have been adapted to wastewater disposal techniques. This method can be utilized with permanent homes in certain portions of the country and may be applicable for summer homes, outdoor recreation areas, highway rest stops and similar installations.

The rate of evaporation occurring in these processes is directly related to the vapor pressure or humidity deficit of the ambient air and is markedly increased at higher temperatures. For this reason, evaporation processes are more feasible for use in the southern portions of the country and also lend themselves to applications for summer homes.

The ET bed and mechanical units used for individual homes are exposed to ambient air and are subject to rain and snowfall. As a result, the precipitation pattern of a specific location has a significant effect on the efficacy of the application of the evaporation concept.

The size requirements of an evaporation unit are directly related to the amount of wastewater generated. Accurate estimates of flow must be made in each design to prevent failure due to undersizing or excessive cost due to flow quantity overestimation. The use of water saving plumbing devices and appliances will result in a direct cost savings in the construction of an evaporative system.

EVAPORATION-TRANSPIRATION BEDS

Two major concepts for ET beds are used; the non-discharging unit where all wastewater is evaporated to the atmosphere and the combination concept where seepage into the adjacent earth materials is utilized in conjunction with evaporation for liquid disposal. Another design consideration is whether some surface runoff is to be permitted during precipitation events. The consideration of these different concepts of design criteria has been termed the acceptance criteria, and the standards for performance are usually set by state or local health authorities.

A survey was made to determine the present use characteristics of ET beds. Approximately four thousand to five thousand ET beds are now in use in the U.S. About three-quarters of these units are of the combination type.

The results of this study are from investigations of the non-discharging type of ET bed. The studies were made using twenty-nine ET bed lysimeters, 53 cm (21 in.) in diameter and 79 cm (31 in.) deep.

Analysis of the results of the lysimeter studies showed that ET beds have only limited capacity for storage of wastewater and cannot store a large portion of the winter loading for later evaporation in the summer. Non-discharging units should be designed at a loading rate equal to the evaporation minus precipitation for the critical year in a ten year span. In order to meet these conditions, the weather conditions in the design area must be such that the evaporation rate substantially exceeds the precipitation rate for every month of the year. This condition exists in a portion of the states of Texas, New Mexico, Arizona, California, Nevada, Utah and Colorado. When the concept is used for summer home applications, the areas that have acceptable climatological conditions can be expanded to include parts of the ten additional states of Oregon, Washington, Idaho, Montana, Wyoming, North Dakota, South Dakota, Nebraska, Kansas and Oklahoma, as shown in Figure 62.

The most reasonable approach to the design of ET beds is with the use of the National Oceanic and Atmospheric Administration (NOAA) weather data for pan evaporation and precipitation. It was found that winter evaporation from nearly full ET beds was approximately the same as measured or estimated for winter pan evaporation. Summer evaporation from nearly full ET beds was about seventy percent of the measured pan value. The mode of operation of ET beds for permanent homes is such that the units have no saturated pore gravity water during long periods in the summer and a low moisture content is held as interstitial capillary water. Summer ET bed evaporation rates are as low as twenty percent of the pan evaporation rate due to the fact that tightly held interstitial capillary water does not rise to the surface and therefore is not evaporated at the same rate as the saturated pore water. It was found in these studies that the moisture content of the bed adjusts itself in such a way that the evaporation rate is fairly constant throughout the year and is about the same as the winter pan evaporation rate.

The type and size of sand used in an ET bed is very important. The sand should be a clean, uniform sand in the size range of D_{50} (fifty percent by weight smaller than) equal 0.1 mm. This type of sand is available in many areas from the settling ponds of gravel washing operations. Capillary rise height and rate tests should be made on ET sand sources before they are selected for use.

The characteristics of the home wastewaters had little effect on the functioning of the ET beds. All units must be preceded with a properly functioning septic tank. Variations in wastewater temperature within the ranges to be expected in the field had no measurable effect on the performance of the system. The wastewater type had no measurable effect on evaporation rate. Primary treated effluent, secondary effluent, and tap water gave essentially the same results when used with the lysimeters.

Approximately seventy-one percent of the annual evaporation from an ET bed was found to be due to the movement of unsaturated air over the surface of the bed. The remaining twenty-nine percent was due to direct sunlight radiation striking the wet sand surface. Selecting surface vegetation for an ET bed to increase ET rates and improve appearance is a difficult task. The very moist, high saturated pore water conditions of the winter and the very dry conditions of the bed in the late summer requires that any vegetation planted on the surface of the bed must have a very high tolerance for wide variations in soil moisture conditions. Most trees and plants, including lawn grass, could not tolerate the moisture extremes. Juniper shrubs and weeds were the only plants that survived the annual soil moisture cycle. In the design of ET beds for summer home applications, the use of fast growing, highly transpiring plants such as alfalfa can substantially increase ET rates.

The appropriate loading rates to be used in the design of ET beds for permanent homes range from 1.2 mm/d (0.03 gpd/ft^2) for areas of eastern Colorado or northern Nevada to 3.2 mm/d (0.08 gpd/ft^2) for southwestern Arizona. Higher loading rates have been reported in the literature but these are usually associated with systems relying on evapo-transpiration plus soil absorption, or are coupled with very high estimates of wastewater generation rates. Loading rates for summer home application range from 4 mm/d (0.10 gpd/ft^2) to 8 mm/d (0.20 gpd/ft^2) or higher.

The health hazards associated with non-discharging ET beds appear to be minimal. Salt build-up in the bed is not a major problem affecting the functioning of the unit, although it may have an adverse effect on surface vegetation after a long period of use. Salt concentrations build up at the surface of the bed during dry summer periods but are redistributed in the pore water throughout the bed after a rainfall event.

The cost of lined, non-discharging ET beds with imported ET sand materials is in the range of $10.00-$15.00 per square meter of surface area ($1.00-$1.50/ft^2). Typical non-discharging ET bed installations range in cost from $3,000 to $10,000 for permanent, individual homes.

MECHANICAL EVAPORATION SYSTEMS

Two types of mechanical evaporation devices were fabricated in small scale and evaluated. Most of the studies were conducted on a multiple rotating disk evaporator (RDE) and a portion of the work involved a rotating cylinder cylinder evaporator (CCE) with multiple wraps of burlap cloth forming the concentric cylinder and with piped air entering the center of the unit. The advantage of the mechanical unit as compared to an ET bed is that a large evaporation surface is created within a very small area for rainfall catchment. This type of unit can be used for evaporation disposal in areas having high annual precipitation.

The mechanical evaporation unit concept can be applied in most locations in the U.S. The unit is preceded by a septic tank and in most areas, a storage vault must also be used. When ambient temperatures drop below 4°C (40°F), freezing of the water on the disks occurs and the unit must be stopped. The wastewater inflow must be held in the vault during low temperature periods. Large vault storage adds significantly to the cost of the system; consequently the most economical applications are in the southern regions where freezing conditions do not occur.

Equations for the design of RDE units have been developed from the small test unit. The major factors in the equations are wind speed and humidity deficit of the ambient air. A minor factor is the solar radiation intensity. These parameters can be established from NOAA weather data for different areas of the country on a monthly basis. Correlation of machine evaporation rate with measured or estimated pan evaporation rate was also made and can be used to estimate unit size for different locations. Sizing of the CCE is dependent on the piped air mass flow rate and humidity deficit and, to a small extent, on ambient air wind speed and humidity deficit as well as solar radiation intensity.

Wind movement over the disks of the RDE maintains the humidity deficit driving force for evaporation. A wind rose (a scaled graphical presentation of surface wind data in terms of speed and direction) should be established for a design location and the unit should be oriented with the disks parallel to the prevailing wind. Wind movement of the unsaturated air is responsible for about 95 percent of the evaporation from the unit. Because of the small size of the unit, direct sunlight striking the disks accounts for only about five percent of the evaporation rate.

The optimization of the machine variables for this type of unit will be a continuing process. Studies on the test unit resulted in some initial findings.

a. The rotational speed of the disks does not have much effect on evaporation rate as long as the speed is great enough to keep the total evaporation surface of the disks wet at all times.

b. The evaporation rate per unit of wetted area is essentially a constant for any set of ambient conditions. The maximum wetted exposed surface area for the RDE exists when the disks are submerged to a depth equal to 0.71 R, where R is the disk radius. This submergence level results in a 75 percent exposed wetted surface and produces the maximum evaporation rate.

c. Optimum disk spacing was found to be at 2.5 cm (1 inch) between centers for the 3 mm (1/8 inch) thickness. At larger spacing, the unit costs increase without providing additional evaporation capacity. At closer spacing the wind movement between disks is retarded and evaporation rate is reduced.

d. Using different disk materials did not affect evaporation rate except when styrofoam was used. Apparently the poor heat conducting properties of styrofoam cause a slightly reduced evaporation rate. The color of the disk had only a minor effect on evaporation. White disks reflected more direct solar radiation and tended to reduce evaporation slightly. The strength characteristics and materials cost should be the important considerations in selecting disk materials.

A brief test was used to indicate the health hazard associated with bacterially contaminated aerosols being carried by the wind from the unit. No fecal coliform bacteria were found at distances greater than 0.15 m (0.5 ft) downwind from the disks. Salt accumulation will occur in the liquid in the storage vault and in the reservoir of the unit. This will require the removal and disposal of some liquid every few years in order to prevent excessive build-up of salts and sludge.

A preliminary cost estimate for an RDE constructed with plastic disks resulted in a total cost of $6300 for the situation of a southern climate where no freezing conditions would exist, to values of $15,000 and higher for northern application where very large vault storage would be required due to extended periods of freezing weather. The cost for summer home applications would be in the range of $4000.

Evaporation systems for wastewater disposal are relatively expensive, especially when compared with soil absorption systems. For design situations in certain parts of the country where alternate systems are required, they may be a feasible option.

The cost analysis for the concentric cylinder evaporator resulted in the conclusion that this type of unit is not economically feasible due to the power costs associated with pumping of the air. The capitol cost of the evaporator is in the same range as that of the rotating disk evaporator but the power cost would be in the order of $0.32/1000 liters ($1.20/1000 gal). The total annual cost would be much higher than for the RDE and it would be unacceptable for nearly all conceivable applications.

SECTION 3

RECOMMENDATIONS

As a result of this study, several recommendations are made to gain improved understanding of the application of the evaporation concept.

ET BED

1. There is a need for studies that would define more clearly the considerations involved in the setting of acceptance criteria for the different types of ET beds.
2. Many individual tests of ET bed systems are being made throughout the U.S. It would be useful for local health authorities if all studies were analyzed, correlated and reported by one national agency.
3. It would be useful if several carefully sealed test units were installed at different locations throughout the U.S. and evaluated under uniform monitoring conditions.

MECHANICAL EVAPORATION SYSTEMS

1. Further work should be encouraged to improve and optimize the design of the RDE. This should include the selection of materials of construction that would reduce the overall cost of the system.
2. Several full scale units should be evaluated at different locations in the U.S.

SECTION 4

BACKGROUND

During the last three decades, strong emphasis has been placed on community sewerage systems and centralized wastewater treatment plants. Much less concern has been shown for the development of new technology for individual home wastewater systems. According to the figures from the 1970 census, twenty-nine percent of the dwelling units in the U.S. are not connected to a central sewerage system and utilize individual home systems. The average number of persons per dwelling unit in the U.S. is almost exactly three people based on the 1970 census data for population and housing units. Using this average figure, a total of approximately 58.5 million people can be considered as the population living in homes that are not connected to a central sewer system. As a comparison, there were 154 cities in the U.S. in 1970 that had populations of over 100,000. The total population of these 154 cities was 55.5 million people. It is apparent that new developments in individual home systems have not kept pace with the rapidly expanding technology for large city sewage treatment systems.

A tabulation of the 1970 census figures by states indicating the number of homes not connected to public sewer systems is shown in Table 1. The data are arranged in descending order, beginning with New York and Pennsylvania which had over a million homes of this type, to the District of Columbia which had only 1325. The bracketed numbers are the percentages of unsewered dwelling units in each state.

Several rurally oriented states in the Southeast and New England have high percentages of population on individual systems. States with over fifty percent reliance on individual systems include Mississippi, North Carolina, South Carolina, Maine, New Hampshire and Vermont. Over one-half of the total number of individual systems in the U.S. are located in the states of New York, Pennsylvania, Michigan, Ohio, Indiana, Illinois, California, Texas and Florida. This indicates that individual systems are used extensively in suburban areas as well as for rural applications. A significant number of individual home units exist in every state. The only exception is totally urbanized Washington, D.C.

TABLE 1. HOME WASTEWATER SYSTEMS IN THE U.S. (1970 CENSUS)

State	Number of Homes not on Public Sewer	Total Homes	Unsewered and not ST-SAS
New York	1,334,136 (22%)	6,158,660	44,883 (<1%)
Pennsylvania	1,081,516 (28%)	3,880,038	96,502 (2%)
Florida	981,095 (39%)	2,490,782	42,743 (2%)
Michigan	897,942 (32%)	2,845,083	50,509 (2%)
California	891,337 (13%)	6,975,969	38,324 (<1%)
North Carolina	885,429 (55%)	1,619,279	197,857 (12%)
Ohio	882,076 (26%)	3,447,393	102,566 (3%)
Texas	819,223 (22%)	3,808,917	164,950 (4%)
Indiana	650,855 (38%)	1,711,597	61,061 (4%)
Tennessee	625,680 (48%)	1,296,928	168,672 (13%)
Illinois	619,683 (17%)	3,691,949	65,080 (2%)
Georgia	618,109 (42%)	1,466,625	143,654 (10%)
Virginia	578,793 (39%)	1,484,823	170,580 (11%)
Alabama	548,484 (49%)	1,114,791	163,139 (15%)
Kentucky	524,184 (49%)	1,060,572	211,328 (20%)
Massachusetts	499,485 (27%)	1,838,789	9,120 (<1%)
Missouri	491,895 (30%)	1,665,583	132,617 (8%)
South Carolina	441,206 (55%)	804,817	106,996 (13%)
Wisconsin	421,116 (30%)	1,416,042	49,549 (3%)
Washington	418,373 (35%)	1,204,924	14,464 (1%)
New Jersey	414,364 (18%)	2,305,346	10,123 (<1%)
Louisiana	367,726 (32%)	1,145,973	80,245 (7%)
Connecticut	360,218 (37%)	968,821	5,633 (<1%)
Mississippi	358,629 (51%)	697,210	149,514 (21%)
Minnesota	354,561 (29%)	1,219,495	47,070 (4%)
Arkansas	317,286 (47%)	672,970	96,999 (14%)
Iowa	288,718 (31%)	955,038	34,829 (4%)
West Virginia	288,628 (49%)	592,779	101,600 (17%)
Oregon	286,503 (39%)	735,478	10,559 (1%)
Maryland	281,000 (23%)	1,234,469	37,271 (3%)
Oklahoma	251,587 (27%)	937,825	48,413 (5%)
Kansas	192,726 (24%)	787,484	28,808 (4%)
Maine	169,726 (50%)	339,200	28,817 (8%)
Arizona	132,446 (23%)	578,750	18,013 (3%)
Colorado	129,979 (18%)	742,638	16,689 (2%)
Nebraska	125,586 (25%)	511,445	20,266 (4%)
New Hampshire	116,246 (47%)	248,721	7,231 (3%)
Rhode Island	109,387 (36%)	307,334	1,843 (<1%)
Idaho	100,412 (42%)	238,303	7,266 (3%)
New Mexico	91,508 (28%)	322,245	25,727 (8%)
Montana	86,172 (36%)	240,753	11,974 (5%)
South Dakota	81,336 (36%)	221,594	18,970 (8%)
Vermont	77,580 (52%)	149,844	9,315 (6%)
North Dakota	71,531 (36%)	200,298	18,457 (7%)
Hawaii	54,402 (24%)	215,891	3,844 (2%)
Utah	53,255 (17%)	311,874	3,976 (1%)
Delaware	44,730 (26%)	174,989	4,870 (3%)
Alaska	33,052 (37%)	88,563	14,423 (16%)
Wyoming	27,566 (24%)	114,549	4,217 (4%)
Nevada	23,939 (14%)	171,682	1,951 (1%)
District of Columbia	1,325 (<1%)	278,343	871 (<1%)
U.S.A.	19,506,167 (29%)	67,693,843	2,909,375 (4%)

SYSTEMS FOR INDIVIDUAL HOMES

The septic tank, soil absorption system (ST-SAS) is used extensively in the U.S. Over eighty-seven percent of the individual systems are of this type. This system has been utilized with few modifications since it was patented by Mouras in 1881. It is a relatively low cost method of disposal that has proven to be satisfactory for many applications. The limitations that may occur with ST-SAS are well known. Soil absorption systems cannot be installed where highly permeable coarse soils or highly impermeable clay soils exist, in areas of shallow soils over fractured rock, steeply sloping topography or high groundwater conditions. Some of these limitations are present in a significant portion of all areas of the country. Where limitations exist, alternate means of disposal are needed. The evaporative disposal techniques provide a means of approaching the problem that can result in no discharge to the ground or surface water environment.

BACKGROUND AND USE OF ET BEDS

The concept of the evaporation-transpiration bed for disposal of home wastewaters developed from studies on the functioning of seepage beds. Studies by Dr. A.P. Bernhart (1964, 1972, 1973, 1974) at the University of Toronto defined the contribution of evaporation in predicting the disposal rate for shallow seepage beds. Design equations have been presented in which the evaporation rate from shallow seepage beds was related to water depth below ground surface, type of soil and vegetation cover on the bed.

Consulting engineers from western states adapted the evaporation data from Bernhart's studies to develop the concept of a total evaporation disposal system for use in areas where severe limitations precluded the use of leaching fields. With the use of an impermeable liner and carefully selected sand, systems have been designed and put into operation that are totally evaporative and non-discharging.

At the present time, the ET bed concept is being used in the design of individual home systems in several states, either on an experimental basis or as an accepted design practice for specialized applications.

Two types of ET bed concepts are in use: (1) the totally non-discharging type and (2) the combination type where both seepage and ET are utilized as the means of disposal.

The first type is utilized where protection of groundwater quality is essential. A continuous liner is placed so as to ensure that evaporation is the only means of water leaving the bed. A carefully selected ET sand is used so that capillary action will raise the water to the surface for evaporation. Most of the rainfall and snowmelt occurring on the unit will drain into the bed and become a part of the water volume to be evaporated. The successful operation of this type of ET system requires that it be applied in areas where meteorological conditions are such that evaporation potential exceeds the precipitation during every month of the year.

The second type, the combination ET-soil absorption system, is designed on the basis that limited percolation will assist evaporation as the water removal mechanism. Combination systems are unlined or partially lined and the water level in the unit is maintained near the ground surface. Precipitation tends to run off of the bed due to the high water level in the soil. This is the type of system studied by Bernhart. His work provided quantitative information on the evaporation portion of the disposal mechanism. Many experimental tests of both types of units are under study in several states by local health authorities.

A published paper by Tanner and Bouma (1975) has reviewed the potential for use of the non-discharging system in Wisconsin. Utilizing the energy balance technique to establish potential evaporation and the annual rainfall pattern in Madison, Wisconsin, they have shown that the system is not feasible in that area because rainfall exceeds evaporative potential. They have also shown with calculations that the use of small trees or shrubs to increase water vaporization by transpiration would not result in enough additional water loss to make the concept feasible in their area. They have also shown with calculations that the biological energy available from the aerobic decomposition of organic matter in the wastewater is insignificant when considered in the evaporation calculations.

Research studies at the University of Wyoming by Hasfurther, et al. (1976) have shown that non-discharging ET beds are feasible in that area for summer use applications. Loadings between 2.6 mm/day (0.06 gallons/day/ft^2) and 10.4 mm/day (0.24 gallons/day/ft^2) were used on a short term, May through July, study.

ET BED APPLICATIONS IN THE U.S.

In order to assess the extent of application of ET beds in the U.S., a questionnaire was sent to the health departments of all 50 states and five Districts and Territories. The survey asked for estimates of the number of ET bed installations of each type and for information on design criteria and legal restrictions on the use of this disposal method.

Forty-three responses were received. The results are shown in four groupings in Table 2. Nineteen state agencies replied that ET beds were not used. All of the states in this category, except Utah, have annual rainfall rates that exceed evaporation potential.

Seven states replied that a relatively small number of units were installed. In most cases it was indicated that the units were experimental in nature. The responses were mostly from eastern states and indicated that agencies within these states are evaluating the concept, using primarily the non-discharging method.

In the regions of the country where ET beds are used more extensively, it is difficult for state health authorities to accurately estimate the number of installed units. Permits for the installation of individual home wastewater systems are normally handled on the county or city level and this information is generally not compiled on a state-wide basis. It can be concluded from the replies in this category that the combination system is used in several eastern states, while both types of units are more common in the semi-arid, western U.S.

In Colorado, the authors estimate that several hundred units of each type have been installed. In Boulder County, which has about five percent of the state's population, over one hundred permits for ET systems have been issued, with approximately one-half of the total for each type of system. The first units were of the non-discharging type and were installed in 1972.

Based on the approximate figures of Table 2, it can be estimated that the total number of ET systems in use in the United States is probably in the range of 4000 to 5000 units, with about three-quarters of the total being of the combination type.

That portion of the questionnaire relating to design criteria for ET systems revealed that this is usually set by local agencies or the design engineer for each system. The criteria developed by Bernhart are used extensively with modifications based on experience gained in local areas. New criteria for design are beginning to appear. The State of Washington has developed very complete guidelines for non-discharging systems that are based on a month by month water balance utilizing localized, ten-year evaporation and precipitation data.

The question relating to legal limitations on ET system use was included in the questionnaire because of a special situation that exists in Colorado. Most states require that the design meet local health authority requirements and conform to general state regulations. In Colorado, a law has recently been passed that creates a class of water wells where the water cannot be used in a completely consumptive manner; that is, some of the effluent must be returned to the ground water or surface water resource. This would exclude the use of a totally non-

TABLE 2. ET BED APPLICATIONS IN THE U.S.
(Health Department Replies)

Group I - ET beds not used.

Alabama
Florida
Hawaii
Illinois
Iowa
Michigan
Minnesota
Mississippi
Missouri
New Hampshire
North Dakota
Oklahoma
Utah
Virginia
Wisconsin
Canal Zone
Puerto Rico
Trust Territory of the Pacific
Virgin Islands

Group II - Small number of applications.

	Non-discharging	Combination
Connecticut	1	15
Delaware	1	2
Kentucky	1	0
Maine	6	0
Nebraska	3	0
New Jersey	2	0
South Carolina	1	0

Group III - ET beds used but estimate of number not available.

Arizona, California, South Dakota

Group IV - ET beds used more extensively.

	Non-discharging	Combination
Colorado	40	30
Idaho	15	30
Montana	20	unknown
Nevada	0	500
New Mexico	70	50
New York	0	200
North Carolina	1	500
Ohio	0	100
Oregon	16	400
Rhode Island	0	200
Texas	300-400 total	
Washington	300	600
West Virginia	10	80
Wyoming	12	12

discharging ET system for homes where this class of water wells is used.

PURPOSE OF THE STUDY

This study was initiated in response to the growing interest in evaporative methods for home wastewater disposal. The purpose was to evaluate the functioning of non-discharging ET beds and mechanical evaporation systems, and establish the relationship between ambient weather conditions and operational and design variables. Design criteria have been developed for ET beds operating under the ambient conditions found in a semi-arid region, where evaporation rate exceeds rainfall values on an annual and monthly basis. In this study, seepage was completely eliminated so that criteria for total evaporative system could be established. Rainfall, snowmelt and freezing weather effects were assessed on a daily and seasonal basis.

One of the limitations of ET bed systems is that the large surface area required is exposed to precipitation. The rainfall and snowmelt entering the unit must be included in the loading placed on the evaporative process. As a result, the feasible application of non-discharging ET beds is restricted to areas where the ET rate substantially exceeds that of precipitation.

The mechanical evaporation unit concept was devised to provide a large surface for evaporation and at the same time have a minimum catchment area for precipitation. The objective was to extend the potential application of the evaporative method to areas of higher rainfall. Two types of mechanical units were evaluated under controlled laboratory conditions and under variable outdoor ambient weather conditions. The rotating disk and the concentric cylinder units were designed to provide a large exposed wetted area for the size of precipitation catchment area, and have a mechanically uncomplicated method of maintaining the wetted surface. The effect of several of the major design variables on the evaporation rate was studied.

CHARACTERISTICS OF HOME WASTEWATERS

The quantity and composition of home wastewater flows are major design parameters for all types of disposal systems. Evaporation systems and seepage methods are sized in direct proportion to the average daily flow. Underestimating the flow will cause failure of the designed system. Overestimating flow will add unnecessary cost and affect feasibility considerations. Since system cost is nearly proportional to flow rate, water saving devices are particularly encouraged in individual homes utilizing evaporative wastewater disposal. Flow reduction must be considered on an individual fixture basis; therefore detailed water use information is valuable. Strength characteristics of home wastes provide information on nuisance and odor potential and can be used for considerations of flow segregation and separate treatment for different waste sources.

The results of several recent studies have shown that the average per capita in-home use of water is approximately 170 liters/day (45 gallons/day). The breakdown of water use by appliance is given in Table 3. It has also been shown in these reports that large families use less water per capita than small families. Bennett and Linstedt (1975) have proposed the formula

$$Q\ (\ell/\text{house/day}) = 225\ (\ell) + 150\ (\ell/\text{adult resident}) + 75\ (\ell/\text{child resident})$$

$$Q\ (\text{gal/house/day} = 60\ (\text{gal}) + 40\ (\text{gal/adult resident}) + 20\ (\text{gal/child resident})$$

TABLE 3. SOURCES OF WASTEWATER FLOWS
(gallons/person/day)

Source	Bennett, et al.	Cohen, et al.	Witt, et al.	Ligman, et al.	Range	Average	%
Toilet	15	13	9	20	9-20	14	32
Laundry	12	8	11	10	8-12	10	22
Bath-total	11				5-12	10	22
tub, shower	(9)	5	10	12		(9)	
sink	(2)					(2)	
Kitchen-total	7	13			5-13	8	18
sink	(5)					(5)	
dishwasher	(1)		5	4		(3)	
garbage disp.	(1)			2		(1)	
Misc.	0	5	8	0	0-8	3	6
Total	44.5	43.8	42.6	47.5	42.6-47.5	44.6	100

On this basis, the average home consumption for design purposes would only rarely exceed 850 ℓ (225 gallons) per dwelling unit per day. This would be equivalent to a family of three adults and two children or two adults and four children. Basing system design on the number of bedrooms and flows of 375 ℓ to 567 ℓ (100 to 150 gallons) per bedroom, as has been done in the past, is unrealistic when viewed in terms of recent water use and family size trends.

Two recent studies by Witt, et al. (1974) and Bennett and Linstedt (1975) have reported similar results for pollutional strength characteristics of home wastewaters. The results of the second study are summarized in Table 4. The average hourly distribution of flow and pollutional strength as measured by COD

TABLE 4. AVERAGE CHARACTERISTICS OF HOME WASTEWATER SOURCES

	Flow/Use (gal)	COD mg/ℓ	BOD mg/ℓ	TOC mg/ℓ	TS mg/ℓ	% Org.	SS mg/ℓ	% Org.	MBAS mg/ℓ	PO_4 mg/ℓ	Total N mg/ℓ	Temp °C	pH
Sink													
Kitchen	1.0	1652	1082		1328	71	209	100	-	1	114	43	6.6
Bathroom	2.0	495	261		480	23	228	100	6	0	1	20	7.9
Average		850	533	370	760	53	215	100	-	1	38	28	7.2
Bath-Shower	27.2	220	100	21	339	6	27	100	53	0	0	38	8.2
Toilet													
Feces (gm/CD)		(34)	(4.7)		(22)	78	(22)	78		(2.2)*	(1.7)*		
Urine (gm/CD)		(13)	(2.2)		(40)	65	[illegible]	0		(0.9)	(3.5)		
Paper (gm/CD)		(18)	(0)		(14.5)	95	(14.5)	95			0		
Average	4.1	1180	124		1400	73	650	85	-	55	95	21	5.6
Washing Machine													
Cycle 1	17.2	1050	400	174	1185	17	128		77	30	8	55	8.5
Cycle 2	4.2	185	46	4	421	6	0		4	3	1	39	7.9
Cycle 3	17.2	130	39	10	527	20	46		2	1	1	55	7.0
Average	38.6	550	200	82	760	16	78	95	35	14	5	53	7.8
Garbage Disp.	2.1	11780	4065		10748	68	6672	95	-	24	285	30	6.4
Dishwasher													
Cycle 1	2.0	620	363	137	2207	20	83		0.3	15	0	58	10.9
Cycle 2	1.0	210	99	47	1083	16	16		0.1	1	0	58	8.3
Cycle 3	2.0	44	23	18	412	3	0		0	0	0	58	7.0
Cycle 4	1.0	35	6	5	75	0	0		0	0	0	58	6.9
Cycle 5	1.0	11	2	0	73	0	0		0	0	0	90	7.0
Average	7.0	225	125	50	920	16	26	100	0.1	4	0	62	7.6
Combined (mg/ℓ)		930	278		1080	55	396	90	15	22	44	36	7.4
Average (#/CD)		0.34	0.11		0.40	0.22	0.15	0.14	0.005	0.008	0.015		
Witt (#/CD)			0.13		0.31	0.19	0.11	0.09		0.009	0.015		

*Literature values

is shown in Figure 5.

A schematic drawing of the flow and pollutional strength proportion from each fixture is shown in Figure 6. It can be noted that black waters (wastes from the toilet and garbage grinder) contribute about three-fourths of the pollutants but comprise only about one-third of the flow. The remainder is contributed by gray waters (wastes from sinks, bathing, clothes washing and dish washing). The idea of separate treatment or recycling of gray waters coupled with evaporation disposal for the black waters could be investigated.

Special fixtures and appliances designed for lowering water use in the home can be very beneficial in reducing the required size of individual home wastewater treatment units. The major water using appliances in the home are toilets, washing machines, bath-showers and sinks. The fixtures presently in use in most homes are designed to provide maximum convenience to the user. Flow reduction could be accomplished in the design of appliances and fixtures without substantially altering the convenience level.

Modern toilets use approximately 15 liters (4 gallons) per flush and the float can be adjusted so that 13 liters (3.5 gallons) are used. Redesigning the tanks and bowl so that 10 liters (2.7 gallons) are required per flush can reduce daily household water use by 90 liters (25 gallons) each day. Other approaches such as dual cycle toilets may reduce water use even further.

Washing machine water use could be reduced by washing only full loads or using the load size selector. The use of a suds saver, where rinse water from previous loads is used as wash water in following loads, is generally not convenient and results in lower wash water temperatures. Modern washing machines have a permanent press cycle that uses about 50 liters (13 gallons) more water than the normal load cycle, 150 liters (40 gallons). From recent studies by Bennett and Linstedt (1975), it was found that washing machine water saving techniques, except for the suds saver, are presently being used in washing machine design. As a result, further water saving with the washing machine does not seem to be available.

Bath and sink water use may be lowered significantly by reducing plumbing pipe and valve size, coupled with smaller bathroom sink and tub sizes. Plumbing pipe and valves are presently of 5/8-inch (1.6-cm) diameter. This size is capable of delivering about 40 liters/min (10 gal/min). It has been found that with a controlled shower head, 4 liters per minute (1 gallon/minute) is adequate for bathing (Bennett and Linstedt, 1975). Smaller piping and valves are required for proper blending of hot and cold water to obtain desired bathing water

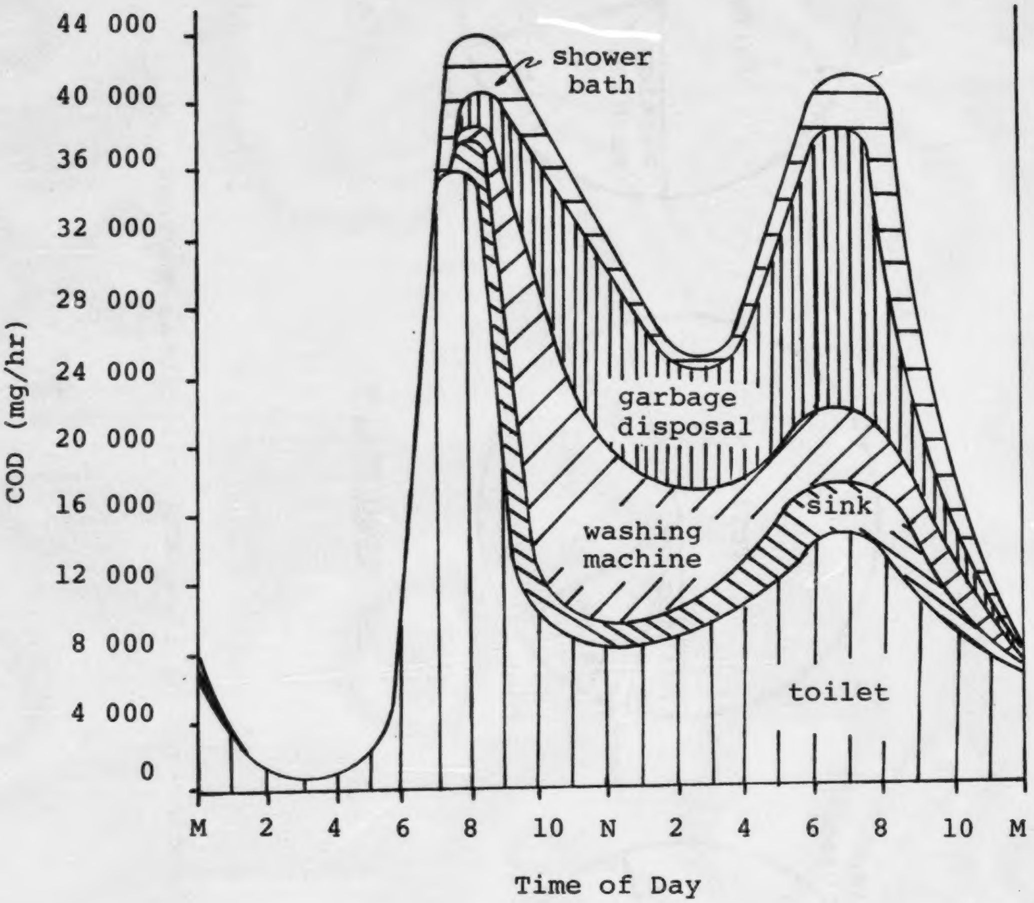


Figure 5. Hourly COD profile.

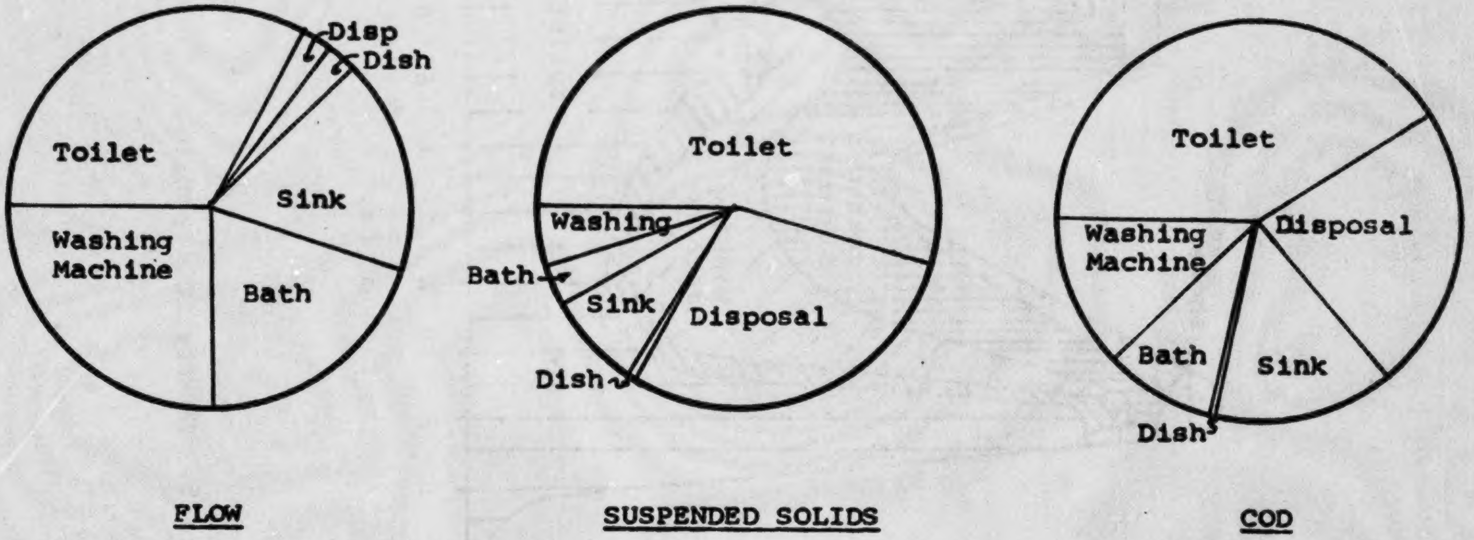


Figure 6. Distribution of flow and pollutional sources.

temperature when the lower flow rate is used. Reduction of bathroom sink and shower plumbing to 0.6 cm (1/4 inch) size could lower water use in these fixtures from 300 liters (80 gallons) to 130 liters (35 gallons) per family per day.

Application of toilet, sink and shower water reduction devices could lower water use by 260 liters (70 gallons) per family per day, based on the normal flow of 850 liters/day (225 gal/day). This represents a 31 percent reduction in wastewater flow. If the concept of flow segregation is used with bath and washing machine wastes being recycled for toilet flushing, the flow can be further reduced by about one-third resulting in less than one-half of the original design flow. The total for these modifications are shown in Table 5.

TABLE 5. DESIGN FLOW COMPARISON WITH REDUCTION AND RECYCLING

	Design Flow without Flow Reduction		Design Flow with Flow Reduction	
	ℓ/house/day	gal/house/day	ℓ/house/day	gal/house/day
Toilet	275	73	185	48
Sinks	142	38	87	23
Garbage Disp.	15	4	15	4
Bath-Shower	162	43	43	12
Dishwasher	19	5	19	5
Washing Machine	218	58	218	58
TOTAL	830	220	567	150
Total with gray water recycle	555	147	382	102

SECTION 5

THEORY

Evaporation is a process governed by the principles of heat and mass transfer. The application of evaporation theory to the understanding and qualitative definition of specific evaporative processes can take several forms. 1) An isolated system can be defined in terms of a constant rate of air movement over a wetted surface. Heat is transferred from the air to the water producing vaporization of the water and transfer of the vapor to the air stream. This approach is termed the mass transport or aerodynamic theory. 2) A system similar to the one above may be subject to external forms of energy such as sunlight radiation. The evaporation due to the supplementary energy source is considered as a separate additive term established on an empirical basis. This approach is termed the combination equation method. 3) Evaporation occurring in an experimental system can be correlated with known or systematically measured evaporation influenced by the same energy sources. Correlations can be made with measured and reported class A pan values or with formulas established by others for evaporation rates established under similar circumstances. The procedure is empirical in nature and is termed the correlation method. 4) Evaporative systems influenced completely by ambient conditions can be formulated using the energy budget theory. An energy balance is formulated based on sunlight radiation, advected energy and water vaporization.

AERODYNAMIC THEORY

The aerodynamic or mass transfer approach is based on the thermodynamic properties of the moving air, those of the wetted surface and the rate controlling conditions at the air-water interface. It is an expression of Dalton's Law in relating evaporation rate, E_{vap}, to a transfer coefficient, k, and the vapor pressure deficit, e_o-e_a, is in the form,

$$E_{vap} = k(e_o-e_a)$$

The driving force for evaporation is the vapor pressure deficit of the moving air, which is the difference between the vapor pressure (e_a) of the ambient air and the vapor pressure (e_o) of the air at the saturation temperature. Humidity deficit,

ΔH, may be used in place of the vapor pressure deficit since they are related through the molecular weights of the air (M_a) and water (M_v) and the total pressure, P, of the air water vapor mixture. The relationship between humidity and vapor pressure is given by,

$$H = \frac{M_v}{M_a}\left(\frac{e}{P-e}\right) = \frac{18}{29}\left(\frac{e}{P-e}\right)$$

For ambient air temperatures and pressures, e is very small with respect to P, and $H = e(0.622/P)$.

The mass transfer coefficient, k, is dependent upon wind speed, air density and pressure and on the roughness of the air-water interfacial surface. Evaporation involves the transport of vapor across a boundary layer. Increase in wind speed decreases the boundary layer thickness and increases the transport rate.

The height used in the measurement of wind speed must be defined. Because of the drag forces produced at the ground surface, wind speed varies in a generally parabolic fashion with height of measurement. Wind speeds at different elevations can be estimated using power law equations based on height.

The mass transfer equation is well suited for formulation of short term measurements of hourly or daily evaporation where humidity deficit and wind speed can be considered as constants throughout the test period. This approach has been used in describing seasonal evaporation but the precision of the calculated evaporation rate is affected by the long term averaging of the highly variable quantities of wind speed and humidity deficit. An early study by Fitzgerald (1886) related field evaporation rate, E_{vap}, to wind speed, W, and vapor pressure deficit, $e_o - e_a$, in deriving the equation,

$$E_{vap}(\text{in/d}) = 0.0166(1 + \frac{W}{2}^{(\text{mph})})(e_o - e_a)$$

Many refinements to this basic form of the equation have been developed since that time.

COMBINATION EQUATION METHOD

The combination equation method is a variation of the aerodynamic theory where direct sunlight effects are included. It is an approximate approach in that it includes an empirical term for the direct solar heating of the water as well as the evaporation from the action of the advected ambient air on the water surface. The method allows for short term evaporation estimates under ambient conditions since it is based on air measurements at any time interval. The equation can be expressed as,

$$E_{vap} = k_1 \Delta H + k_2 R_s$$

where k_1 and k_2 = constants

R_s = sunlight radiation

ΔH = humidity deficit of the ambient air (Δe and ΔH are interchangeable if the constants are adjusted)

Some of the most frequently used field and lake evaporation formulas are of the combination type.

Penman (1963) - Field

$$E_{vap} = \left(\frac{\Delta}{\Delta+\gamma}\right)(R_s+G) + \left(\frac{\gamma}{\Delta+\gamma}\right) 15.36 (1.0 + 0.0062\ W)(e_o-e_a)$$

where E_{vap} = mm/day

Δ = slope of sat vap press - temp curve (mb/^{o}C)

γ = psychrometric constant (mb/^{o}C)

G = heat from ground (cal/cm^2/day)

W = wind speed (km/d)

R_s = net radiation (cal/cm^2/day)

e_a = vapor press (mb)

e_o = sat vapor press (mb)

Kohler, Nordensen, and Fox (1954) - Lake

$$E_{vap} = 0.7 \left[\frac{\Delta}{\Delta+\gamma} R_s + \frac{\gamma}{\Delta+\gamma} (0.37 + 0.0041\ W)(e_o-e_a)^{0.88}\right]$$

Same definitions except English system.

Van Bavel (1966), Businger (1956) - Potential Field

$$E_{vap} = \left(\frac{\Delta}{\Delta+\gamma}\right)(R_s+G) + \left(\frac{\gamma}{\Delta\ \gamma}\right) \frac{0.622 \times \rho K^2}{P} \frac{W}{\ell n \frac{z}{z_o}} (e_o-e_a)$$

where z = elevation above ground of wind speed measurement (m)

z_o= roughness length (m)

ρ = air density (gm/cm^3)

P = atm pressure (mb)

K = von Karman constant

CORRELATION METHOD

An approach that is useful for studying the effect of variation in design parameters under controlled conditions is the comparison of empirical evaporation rate with that of the standard evaporation pan. In this way, the effect of each parameter can be judged against a baseline evaporation resulting at the same site and under the same meteorological conditions. The technique is useful for long term studies where measurement of actual pan evaporation is more representative than values calculated from equations using long term averages of weather parameters.

Pan evaporation data are also useful for determining potential application of evaporative disposal systems for different locations in the country. Standard pan evaporation data are available throughout the nation and provide an excellent means of comparison, based on actual evaporation measurements. The National Oceanic and Atmospheric Administration (NOAA) publishes pan evaporation data for more than 100 stations throughout the United States. The validity of the formulations derived from the results of other research techniques is often based on comparison to recorded pan data. Where pan data are not available, they can be estimated from the formulations resulting from research studies. These types of equations are summarized in technical publications such as ASCE Technical Committee (1974) and Gray (1970). Evaporation from lakes and saturated soils has been found to be in the range of seventy to eighty percent of the pan evaporation measurement.

ENERGY BUDGET THEORY

The energy budget method defines evaporation rate as a function of the energy available from sunlight and may be written to include energy advected to the system with the water. The total energy that the sunlight imparts can be written as,

$$\varepsilon_{ST} = \varepsilon_{evap} + \varepsilon_{reflect} + \varepsilon_{longwave\ ex} + \varepsilon_{boundary} + \varepsilon_{internal} + \varepsilon_{temp\ loss} - \Delta\varepsilon_{advected\ H_2O}$$

where ε_{ST} = total solar radiation reaching the evaporation surface

ε_{evap} = energy utilized in water evaporation

$\varepsilon_{reflect}$ = reflected solar radiation

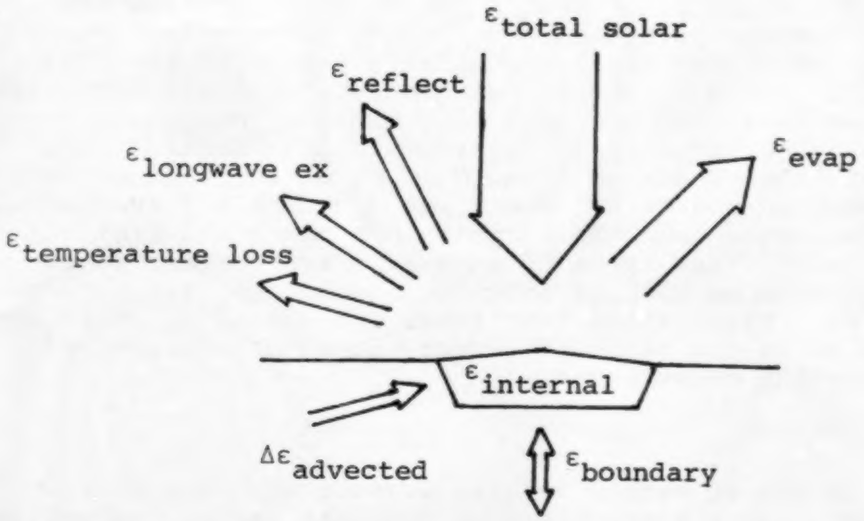
$\varepsilon_{longwave\ ex}$ = net longwave radiation exchange between atmosphere and wetted surface

$\varepsilon_{boundary}$ = energy lost or gained from the earth

$\varepsilon_{internal}$ = energy stored or lost by the materials of the evaporation system

$\varepsilon_{temperature\ loss}$ = sensible heat loss to the atmosphere

$\Delta\varepsilon_{advected}$ = energy brought in by water entering the system


$\varepsilon_{total\ solar}$
$\varepsilon_{reflect}$
$\varepsilon_{longwave\ ex}$
ε_{evap}
$\varepsilon_{temperature\ loss}$
$\varepsilon_{internal}$
$\Delta\varepsilon_{advected}$
$\varepsilon_{boundary}$

For most analyses, $\Delta\varepsilon_{internal}$ and $\varepsilon_{boundary}$ are very small and difficult to estimate and are therefore not included in the balance. The advected energy, $\Delta\varepsilon_{adv}$, involves a liquid materials balance and for most problems, it can be considered an insignificant value. Advected energy is important for large water bodies, such as with lake evaporation, but is a very small value for ET beds or mechanical evaporation units.

The total short wave solar radiation (ε_{ST}) reaching an area on the earth can be estimated by determining the total potential radiation and applying an empirical cloudiness coefficient. The total potential radiation (ε_{R}) reaching the earth is known and is tabulated in many sources as a function of latitude. The relationship between ε_{ST} and ε_R as a function of the cloudiness factor has been estimated by Penman (1948) and others to be of the form $\varepsilon_{ST} = \varepsilon_R(a + bC)$. The empirical constants have been found to be in the range of a = 0.2 and b = 0.55. The function, C, is the ratio of cloudless hours to total sunshine hours available.

A portion of the sunlight reaching the earth is reflected instead of being absorbed. The fraction reflected, expressed as a reflectance coefficient (r), is dependent on the surface cover. The value of $\varepsilon_{reflect}$ can be estimated from,

$$\varepsilon_{reflect} = \varepsilon_{ST} r$$

Reflectance coefficients (albedo) are unique for each surface but are in the range of 0.15 for soils and planted fields, 0.1 for water surfaces, 0.5 for ice and 0.8 for snow cover.

The earth emits longwave radiation, and much of this interacts with the atmosphere and returns to the earth. The longwave or black body radiation escaping the atmosphere can be estimated from the product of the Stefan-Boltzman coefficient and the earth surface temperature raised to the fourth power. This must be modified by the emissivity, m, which is the ratio of recaptured radiation to total longwave emission, a different cloudiness function, f'.

$$\varepsilon_{longwave\ exchange} = \sigma T^4 (m-1) f'$$

where $\sigma = 1.17 \times 10^{-7}$ cal/cm^2/$^\circ$K^4/day

$m = a + b\sqrt{\text{vapor pressure air (mb at 2 m)}}$

a & b = empirical coefficients

f' = 0.97 (for H_2O) to 1.0

The energy from water temperature loss to the atmosphere is very difficult to measure. An approach has been presented by Bowen (1926) with the following expression,

$$\varepsilon_{temp\ to\ atm} = \varepsilon_{evap} (\text{const} = 0.61) \times \left(\frac{\text{Temp } H_2O - \text{Temp air } (^\circ C)}{\text{sat vap press} - \text{vap press air (mb)}}\right)\left(\frac{\text{pressure (mb)}}{1000}\right)$$

Once all of the values in the energy budget have been estimated and a sum produced, the remaining energy can be equated to the potential evaporation for a given volume of water by dividing by the heat of vaporization of water. The heat of vaporization can be expressed as $H_v = 596 - 0.52$ (temp of H_2O in ^{o}C) or approximately 585 to 590 cal/gm. Evaporation can occur directly from ice but the rate is reduced and the heat of vaporization is in the range of 680 cal/gm (Tanner and Bouma, 1975). An example of the calculation of potential evaporation using the energy budget approach has been presented in the article referenced above.

The energy budget method is theoretically sound but the application involves empirical coefficients and estimation of many factors. For this reason and because of the difficulty of establishing the small variations in parameter values with time that are needed for correlation with research measurements, the method is applicable to general types of problems but difficult to use for the correlation of research measurements.

APPLICATION OF THEORY TO ET SYSTEMS

Research studies on the functioning of ET beds involve long term evaluations. The changes in evaporation rate on a seasonal basis and analysis of the performance over the complete annual weather cycle are important. Detailed studies of design variables can be made for each month of the year. Measured pan evaporation data are used for the research and design correlation analyses because they provide the degree of sensitivity required for long term studies at a specific location. The use of measured pan evaporation data in research studies provides a reference evaporation rate that is determined under identical weather conditions and one that can be used to assess the effect of each variable being studied. In design, the use of pan evaporation data provides a means of comparison between different locations throughout the country and also allows for an assessment of the ranges of evaporation rates that have occurred at a location over a period of many years. It would be very difficult, using the empirical equations or the energy balance method, to obtain similar reliability for the reference data because of the long term averaging of meteorological data and the assumptions that must be used with those techniques.

All of the weather stations that provide pan evaporation measurements reported in the NOAA summary also record rainfall data. The weekly or monthly rainfall amounts can be used in the design analysis of an ET system.

In this report, correlations of research data were made with pan evaporation and rainfall measurements obtained at the research site. The design analyses for different locations in the country are based on measured values from weather stations reported in the NOAA monthly summaries.

APPLICATION OF THEORY TO MECHANICAL SYSTEMS

The research studies with the mechanical evaporation units involved detailed analyses of each of the design parameters. For each design variable, a series of tests was run under controlled conditions to establish an equation or functional relationship for different values of that parameter. Each of the test periods was of relatively short duration, two to twenty-four hours. This time period was used so that essentially steady state conditions, with respect to the weather variables, could be maintained during each test.

The functioning of the mechanical units is basically the same in theoretical concepts as that of the aerodynamic and combination equation evaporation theories. Evaporation results from the movement of unsaturated air over a wetted surface. The driving force for the vapor transport is the adiabatic humidity deficit of the air and the rate of evaporation can be defined with a film transfer coefficient and the principles of psychrometry. A psychrometric chart is used to establish the humidity deficit based on the temperature and relative humidity of the air moving through the evaporator.

The aerodynamic theory was used in the analysis of the data for the rotating disk evaporator. Some of the studies were made in the outdoors where direct sunlight effects were present and therefore the results were analyzed in a combination form equation of the following type,

$$E_{vap} = k_1 \Delta H + k_2 R_s$$

The transport coefficient, k_1, includes the effects of wind speed and includes the effects of geometric variables of the unit design. The coefficient, k_2, relates the effectiveness of capture of the direct sunlight energy.

The operation of the concentric cylinder evaporator can be defined with a similar basic theory except that the effects of the compressed air introduced to the unit are considered in addition to the ambient air and sunlight parameters. A combination equation of the following form is used,

$$E_{vap} = k_1 \Delta H_1 + k_1' \Delta H_2 + k_2 R_s$$

The term ΔH_1 represents the humidity deficit of the ambient air, and ΔH_2 for the compressed air. The transport coefficient, k, was evaluated for the effects of wind speed and machine design variables, k_1', includes a compressed air mass flow rate term and k_2, is the direct sunlight proportionality term.

The design concepts for both types of mechanical evaporators involve the application of the combination equations and pan evaporation correlations.

PSYCHROMETRIC CHARTS AND WET BULB THEORY

Evaporation is a process of simultaneous heat and mass transfer. At the air-water interface the temperature adjusts such that, at steady state, the rate of heat transfer required for the phase change of the water is balanced by the rate of moisture vapor mass transfer. Evaporation produces a lowering of the sensible heat of the water causing heat flow from the air to the water. When equilibrium is attained, the temperature of the water is the wet bulb temperature. The transfer of heat as water vapor from the water to the air can be expressed as,

$$q = \lambda_{TW} W_w$$

where q = rate of heat flow

W_w = mass of water vaporization with time

λ_{TW} = latent heat of vaporization at wet-bulb temperature

The rate of mass transfer of water vapor across the interfacial boundary is,

$$W_w = K_g A M_v (e_w - e_a)$$

where A = interfacial area

K_g = mass transfer coefficient

M_v = molecular weight of water vapor

e_w = vapor pressure at wet bulb temperature

e_a = vapor pressure of air

At ambient temperatures where vapor pressure is small compared to total pressure of the gas phase,

$$e_a = \frac{M_a}{M_v} PH$$

where M_a = molecular weight of air

P = total pressure of air

H_a = humidity of the air

H_w = humidity at wet bulb temperature

and the equations combine to,

$$q = K_g A M_v \lambda_{TW}(e_w - e_a) = M_a P K_g A \lambda_{TW}(H_w - H_a)$$

The rate at which heat flows to the water is,

$$q = h_g A(T_a - T_w)$$

where h_g = heat transfer film coefficient

T_a = temperature of air

T_w = temperature of wet bulb

At equilibrium the two heat transfers are equal and

$$H_W - H_A = \frac{h_g}{M_a P K_g}\left(\frac{T_a - T_w}{\lambda_{TW}}\right)$$

In the adiabatic process the temperature of the water in contact with ambient unsaturated air will drop causing heat flow from the air to the water and vapor transport to the air. If the contact time is relatively long and equilibrium exists, the temperature of the water surface will become equal to the temperature of the saturated air. Unsaturated air moving across the wet surface will drop in temperature and gain humidity as the evaporation process takes place. The driving force for the transfer will be the humidity deficit of the entering air. A heat balance for the adiabatic cooling of the air is

$$G_G C_s(T_a - T_s) + G_s H_a \lambda_s = G_G H_s \lambda_s$$

where G_G = mass velocity of the unsaturated air per unit area of wetted surface

C_s = heat of the entering air

λ_s = latent heat of vaporization at saturation humidity

T_s = air temperature at saturation

Rearranging the above equation gives

$$H_s - H_a = \frac{C_s \; T_a - T_s}{\lambda_s}$$

By combining the two expressions for ΔH,

$$\left(\frac{H_w-H_a}{H_s-H_a}\right)\left(\frac{T_a-T_s}{T_a-T_w}\right)\left(\frac{\lambda_s}{\lambda_{TW}}\right) = \frac{h_g}{M_a P K_g C_s}$$

The expression on the right side is the psychrometric constant and has been found to have a value near unity (Rich, 1961). This allows the use of adiabatic saturation temperature to be determined directly from the wet bulb reading. The psychrometric chart is a plot of saturation humidity as a function of temperature. A family of lines is drawn at percentages of saturation. Lines indicating temperature and humidity change for an adiabatic process can be constructed as straight lines with the slope of C_s/λ_s. Charts are slightly different for high altitude areas because pressure is a function in the psychrometric constant. A chart for the elevation of Boulder, Colorado (1700 meters) is shown in Figure 7.

Entering the chart with ambient temperature and relative humidity (T = 25°C (77.5°F), RH = 10% in the example), the humidity of the air can be determined. The adiabatic saturation humidity (2.2 gm/kg) is found by following the adiabatic line to the saturation line and reading the humidity (8.7 gm/kg). The humidity deficit is the difference of the two readings.

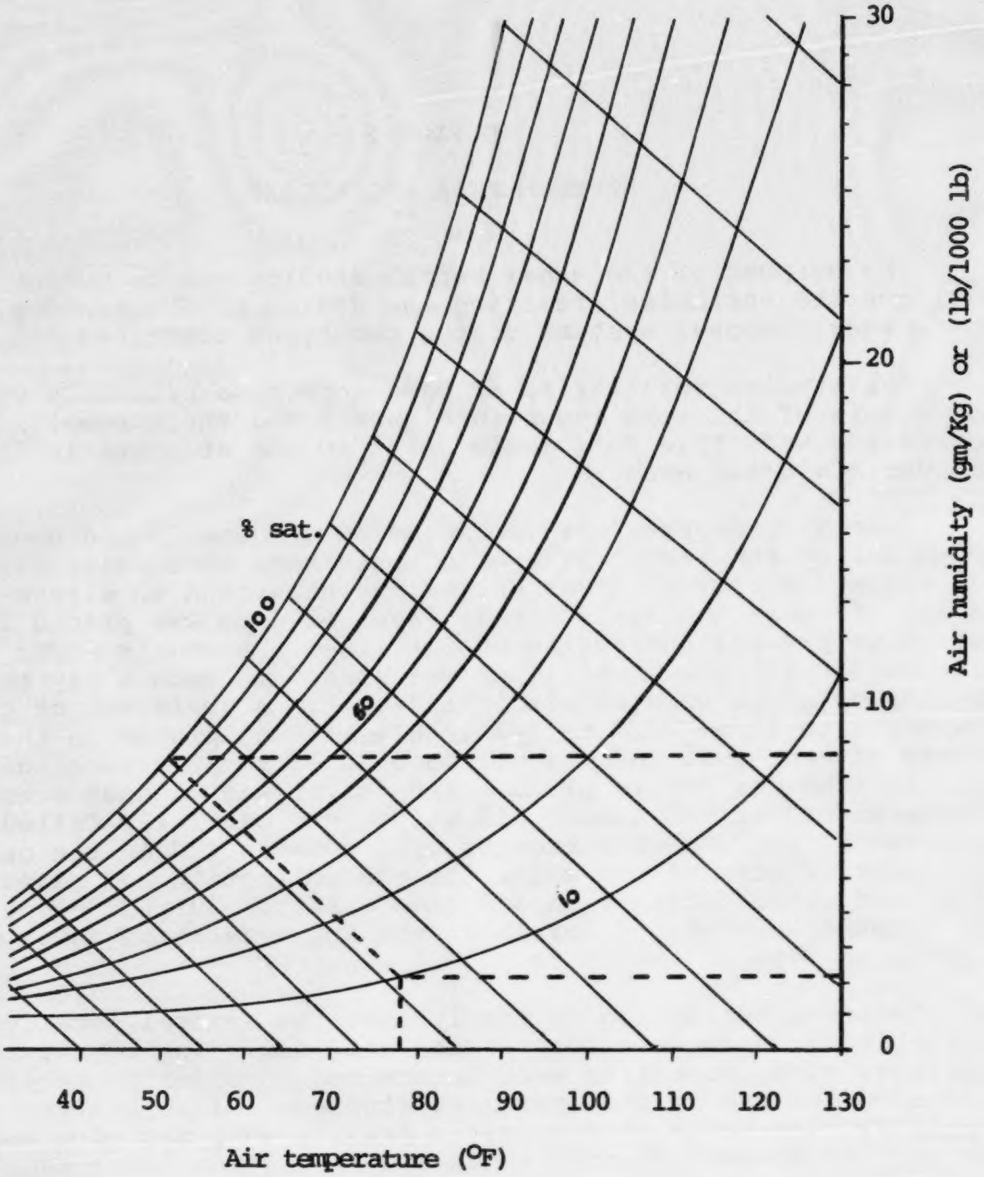


Figure 7. Psychrometric chart for Boulder, Colorado elevation

SECTION 6

EXPERIMENTAL PROCEDURES

The purpose of the experimental studies was to define and evaluate the variables affecting the design of evaporative wastewater disposal systems of the two types described.

The studies relating to ET beds were made primarily with lysimeters of the type shown in Figure 2 and these results were correlated with five full scale units in use at homes in the Boulder, Colorado area.

Twenty lysimeters were constructed originally and nine were added during the study. The main containers were water tight 55 gallon (208 liter) drums buried in the ground to within 7.5 cm (3 in) of their top lip. A thin layer of sand was placed in the bottom to prevent puncturing of the liner. A double layer of 0.15 mm (6 mil) polyvinyl liner was placed in such a way that no opening or seams existed within the unit. A small amount of gravel, 6 to 12 mm (1/4 to 1/2 inch) size was placed in the bottom of each unit and the ell shaped, 18 mm (3/4 inch) diameter filling tube was put in place. The gravel was mounded over the discharge end of the tube. All units were carefully filled with selected ET sand. Drain troughs were constructed on the outer perimeter of some of the units for the collection and measurement of runoff water during rain and snow events. Surface slopes of the ET sand were shaped for each unit and vegetation cover was planted on some of the units.

Before construction of the lysimeters, several locally available ET sands were located and analyzed. The physical and capillary rise properties were determined in order to select the best sand for use in the lysimeter studies. Sieve analyses, capillary rise tests, and specific gravity analyses were made for each of three different sands available from local suppliers.

Two of the sands were produced from the settlement of washwater used to clean mortar sand at local sand and gravel suppliers. The third was from a natural deposit of wind eroded materials mined in the local area. It is referred to as "windblo".

Sieve analyses, consisting of mechanical shaking of a 500 gm sample of sand that had been dried and separated into individual particles was accomplished with ten minute shaking through a stack of U.S. standard sieves of number 40, 60, 80, 100, 140 and 200 mesh. The particle size distributions determined are shown in Figure 8 for the sands from the Golden Sand and Gravel Company, C-M Sand and Gravel Company and the wind-blo deposit. Two of the sands had a D_{50} (mean particle diameter) in the desired range of 0.1 to 0.15 mm. The C-M was a slightly finer, more poorly graded sand. The wind-blo was a more coarse and more uniform sand.

Samples of each sand that had been dried and separated into individual particles with a mortar and pestle were used in a capillary rise test. Clear plastic vertical tubes of 2.54 cm (1 inch) inside diameter were filled with each of the sands. The lower ends of the columns were in a pan that was filled with water during testing. Six different samples were tested with tap water and with primary effluent from a local wastewater treatment plant. The six samples consisted of each of the three sands and fractions of the Golden and C-M sands. Two of the fractions consisted of the C-M and Golden sands with all particles of less than 75 μ (200 mesh) removed. The sixth sample was the combined materials of less than 200 mesh for the C-M and Golden sands.

The water was added to the pan at the base of the columns and the height of the wetted water level was recorded with time for a period of ten days. The results of the capillary testing are shown in Figures 9 and 10. It was found that the capillary rise rate for tapwater and primary effluent were identical.

After the water movement had reached equilibrium at ten days, the moisture content as a function of height of rise was determined for the C-M and Golden sands by carefully removing a series of five centimeter portions from the top of the columns and measuring the weight of water and weight of dry sand. A drying and weighing procedure was used. The results of this analysis are shown in Figure 11.

In order to determine the void ratio and percent saturation of the water in the lysimeters, the specific gravity of the sand particles was measured by using the procedure described by Lambe (1951). The specific gravities of the sand particle solids were found to be nearly identical at a value of 2.69.

The sand from the Golden Sand and Gravel Company was selected for the lysimeter studies. The capillary rise tests resulted in a height of rise slightly greater than the depth of the bed used in the lysimeters and in field units. The beds were 0.7 meter (28 in.) deep. Golden sand was used in most of the in-place beds selected for the field study correlation.

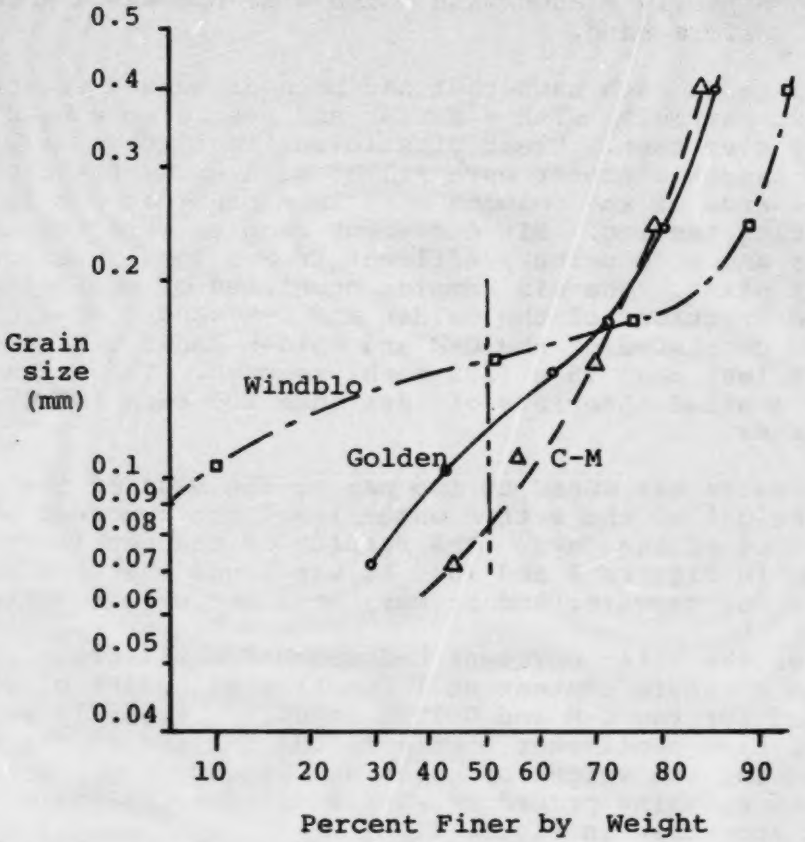


Figure 8. Gradation analysis for three samples of ET sand.

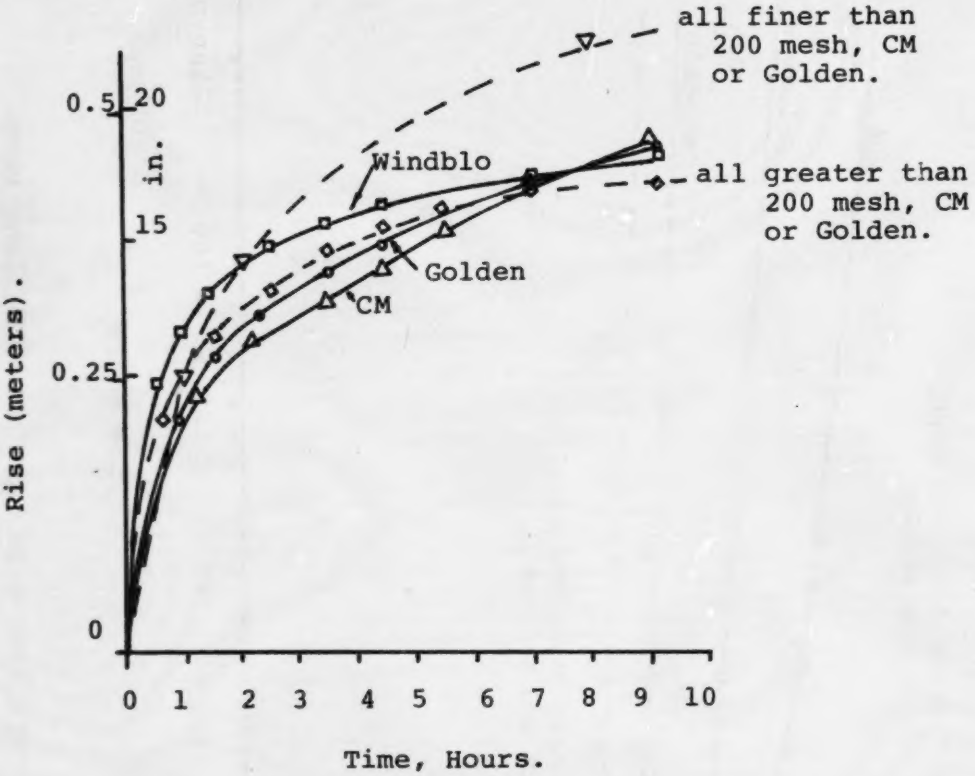


Figure 9. Capillary rise test results (10 hour)

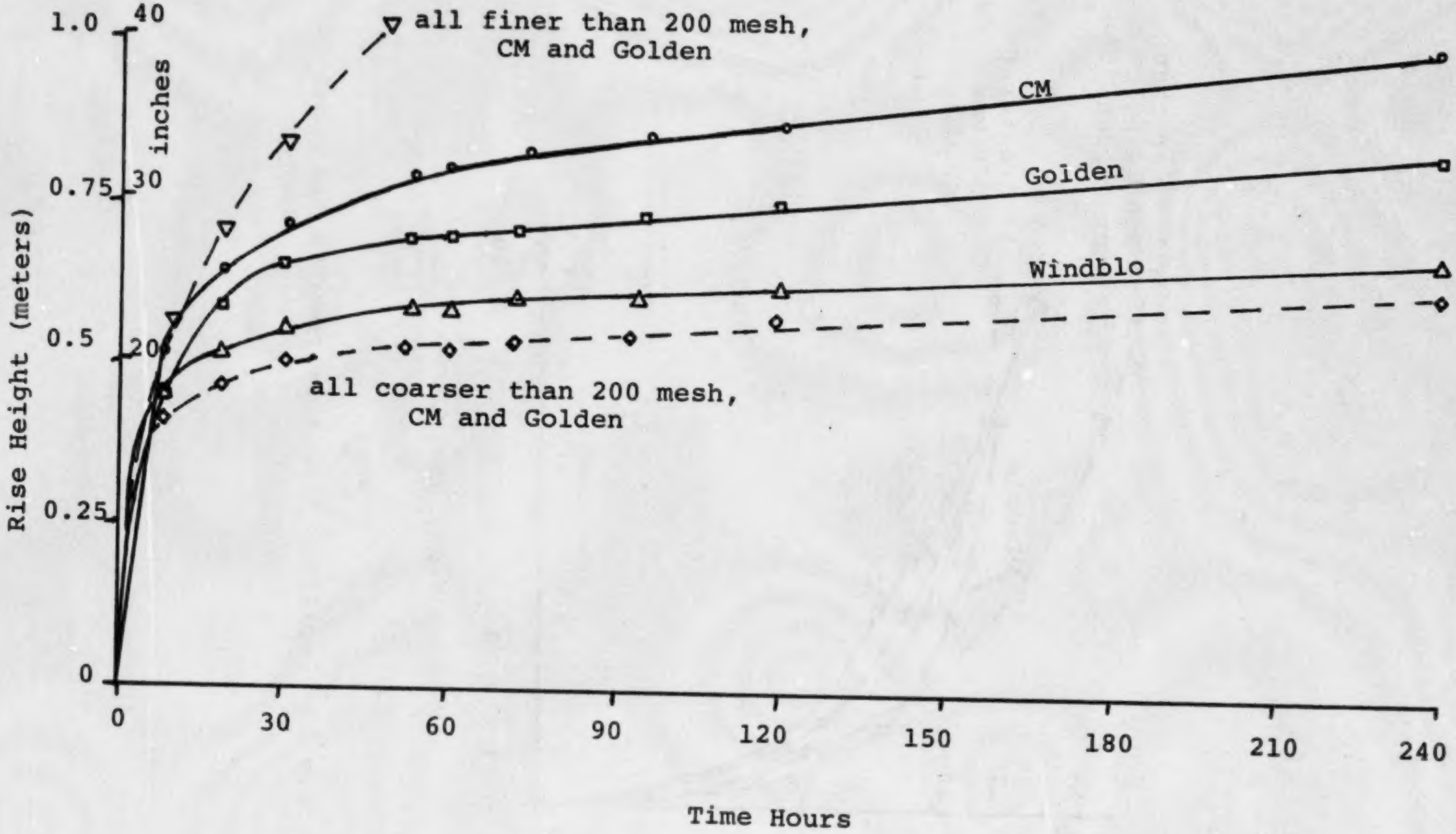


Figure 10. Capillary rise test results (long term)

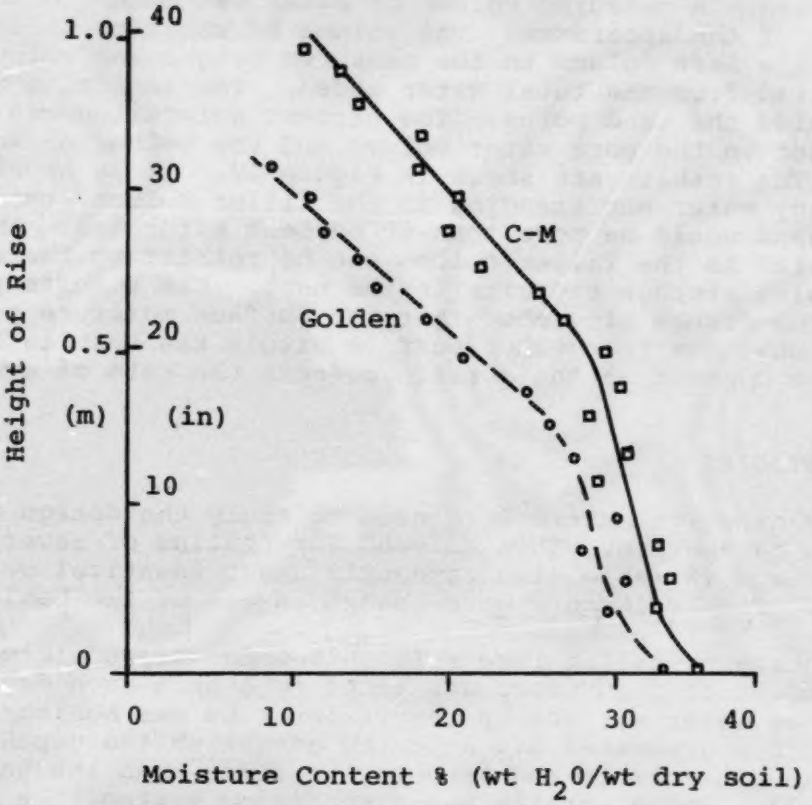


Figure 11. Moisture content of sand column as a function of height above free water surface.

One further test of the sand was made prior to filling the lysimeters. This was done to establish the relationship between the water table level, as measured by the height of standing water in the lysimeter filling tube, and the degree of saturation of water in the sand. The apparatus used is detailed in Figure 12. The sand was tapped into place and the water level in the opposite column was measured after the water movement had come to equilibrium. Two water levels were used and the moisture content was measured at 5-cm levels in a similar manner to previous tests. A measured volume of water was added to the left column of the apparatus. The volume of water to fill the tubing and the left column to the measured height was calculated and subtracted from the total water added. The remaining water added occupied the sand pores. The percent saturation was calculated based on the pore water volume and the volume of void, as shown. The results are shown in Figure 13. It is apparent that when any water was standing in the filler column, the lysimeter sand would be more than 80 percent saturated. The depth of water in the filler column can be related to the available remaining storage capacity in the unit. The results presented in the figure also show that the surface moisture content is reduced when the free water surface within the unit is lowered. The moisture content at the surface affects the rate of evaporation.

LYSIMETER STUDIES

Twenty-nine lysimeters were used to study the design and operational parameters. This allowed for testing of several values for each variable simultaneously under identical weather conditions. The lysimeters were loaded in one of two basic ways.

1. Constant loading rate - In this mode, a predetermined amount of feed water was added to a unit each day. The free water surface in the filler tube was monitored with a graduated dip stick to establish the depth of the water table and to note the times when the unit was full. For a totally non-discharging system, the full condition represented overloading and failure of the unit for that design parameter.

2. Constant water level - In order to compare relative evaporation rates of different types of surface cover, water table depth, etc., a variable amount of feed water was added to a unit each day in such a way as to maintain a nearly constant standing water level in the filler tube. The amount of water added was a direct measure of the amount of water evaporated over the previous period.

The lysimeter units were operated for twenty months. During that period, parametric studies of several variables were

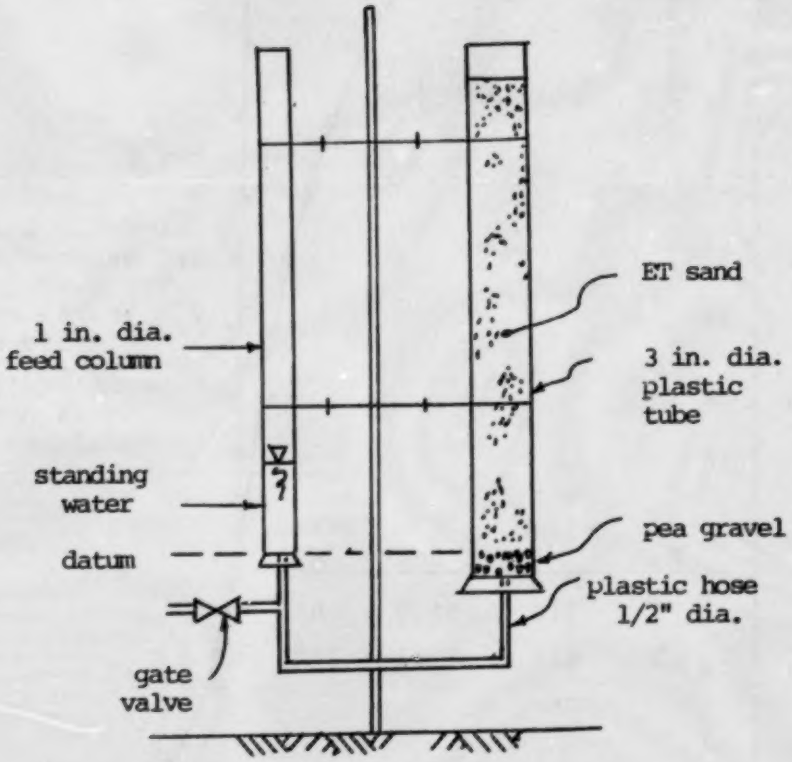
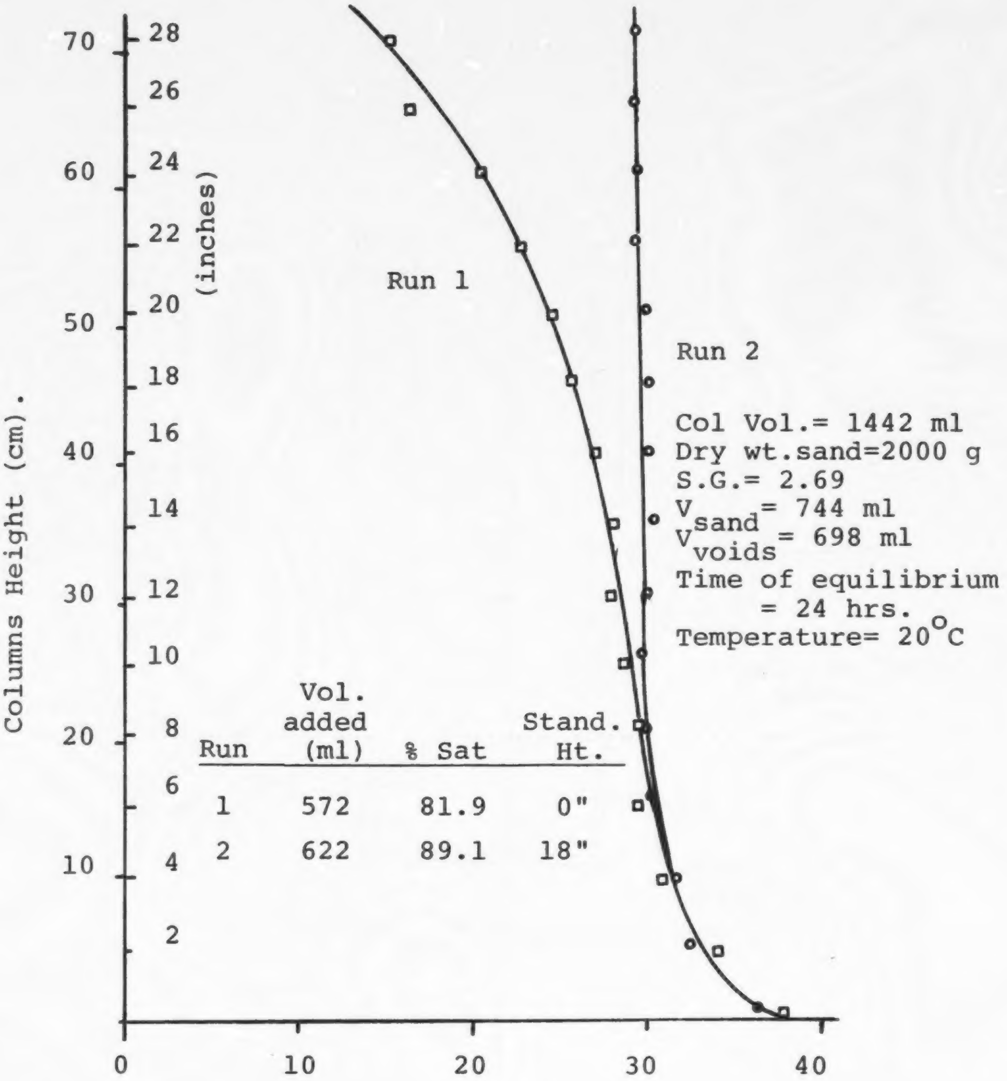

ET sand
1 in. dia.
feed column
3 in. dia.
plastic
tube
standing
water
pea gravel
datum
plastic hose
1/2" dia.
gate
valve

Figure 12. Apparatus used to relate water table and saturation.



Run	Vol. added (ml)	% Sat	Stand. Ht.
1	572	81.9	0"
2	622	89.1	18"

Col Vol.= 1442 ml
Dry wt.sand=2000 g
S.G.= 2.69
V_{sand}= 744 ml
V_{voids}= 698 ml
Time of equilibrium
= 24 hrs.
Temperature= 20°C

$$(\text{M.C.} = \frac{\text{wt. of } H_2O}{\text{wt. of dry soil}} \times 100\%)$$

Figure 13. Moisture content of sand as a function of the height of free standing water.

completed. Some of the studies were made for the full time period while others were shorter term. For all studies (except for the one noted), the wastewater utilized was primary effluent from the Boulder sewage treatment plant. The wastewater was stored for four days prior to use. The wastewater was a readily available source that simulated the quality of septic tank effluent.

The major considerations affecting the design of ET beds are the type and size distribution of the ET sand and the loading rate. The other parameters evaluated provided insight to the functioning of the units and were used to explore the effects of construction features. The variables in the studies were as follows:

1. Wastewater loading rate - The wastewater feed rate was varied from 0.00 mm/day to 8.15 mm/day (0.20 gal/day/ft^2 or 8.15 liter/day/m^2) for different units. Each unit had a constant loading rate. The loading rates used were 0.00, 0.41, 0.82, 1.23, 1.63, 2.05, 2.45, 3.26, 4.07, 6.52, 8.15 mm/day which are equivalent to 0.00, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08, 0.10, 0.16 and 0.20 gal/day/ft^2. Golden ET sand was used in all units. Each had a bare, unplanted, sand surface with a slope of 1:6 (vertical:horizontal). Wastewater temperature was 30°-37°C, the temperature of combined wastewater generated in the individual home.

2. Depth of free water surface - The moisture content at the surface of a unit has been shown to be greater when the standing water level is high and less when the water level is reduced. Six static water level lysimeters were used to evaluate the effect on evaporation rate as a function of standing water depth in the unit. The levels used, as measured from the ground surface downward were 0, 12.7, 22.9, 33.0, 45.7, and 58.4 cm (0, 5, 9, 13, 18, and 23 inches). The total unit depth was 68.6 cm (27 inches). The lysimeters were identical to those described in #1 except that the water level was determined each day and a sufficient volume of water was added to maintain a nearly constant level on a day to day basis. The standing water level and the volume added were measured and recorded daily.

3. Rainfall and sunshine effects - Special covers were constructed over four of the units. They are shown in Figure 14. The top surfaces on two of the covers were made of clear lucite, to allow sunlight to reach the bed surface but to preclude rainfall. The tops of the other two covers were made of plywood to eliminate sunlight and rainfall. The sides of the covered structures were open and wind movement over the lysimeter surface

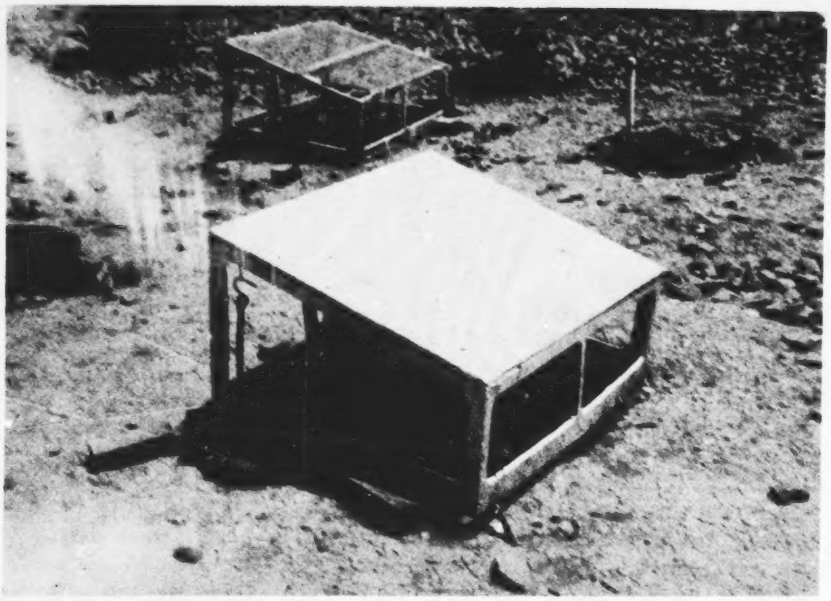


Figure 14. Test lysimeters with clear and opaque covers.

was not inhibited. The unit construction was identical to that described in #1.

One of the lucite covered and one of the plywood covered units were loaded at 1.63 mm/day (0.04 gal/day/ft^2) so that the results could be compared with the uncovered units described in #1 in order to establish the effect of sunlight and rainfall. The second lucite and plywood units were kept at a constant free water level of 22.9 cm (9 in.) below the bed surface so that comparative evaporation rates could be established with respect to the uncovered units described in #2.

4. Surface slope runoff effects - A portion of the rainfall landing on an ET bed will run off and not become a part of the liquid loading. The amount of runoff from the lysimeters was evaluated by using three different surface slopes: flat, 1:6 and 1:2. The units were identical to those in #1 except for surface slope. Each unit was provided with a small, aluminum gutter along the periphery that discharged into a collection bottle. After each rain, the amount of runoff collected was measured volumetrically.

5. Soil grain size - Two lysimeter units were filled with ET sands that were sieved to produce different capillary characteristics. Golden ET sand was dry sieved through a 100 mesh (0.15 mm) screen. One unit was filled with the material whose grain sizes were all greater than 100 mesh and the other unit was filled with all material less than 100 mesh. Evaporation rates were measured under the conditions of a constant static water level. Two different levels were used at different times in the study: 22.9 cm (9 inches) and 58.4 cm (23 inches) below the bed level.

6. Wastewater temperature - One lysimeter constructed to be identical to those in #1 was fed wastewater at an elevated temperature of 50°C, and a constant rate of 1.63 mm/day (0.04 gal/day/ft^2). This unit was compared with a similarly loaded lysimeter with wastewater temperature of 30°-37°C.

7. Type of wastewater - Near the end of the study, six lysimeters were used to establish if different performance could be expected from influent wastewaters which had received different degrees of treatment. All units were identical to those of #1 except that two units were loaded with primary effluent, two with well treated secondary effluent and two with tap water. With each pair, one was held at a static water level of 22.9 mm (9 inches) and one at 58.4 mm (23 inches) below the

sand surface. The free water surfaces were maintained at a relatively constant level, and therefore the volume of water added each day was equal to the evaporation rate. The evaporation from all units was compared and related to the measured pan evaporation rate. The average characteristics of the waters used based on the records of the Boulder water and wastewater utility for the study period were as follows:

	Ave. BOD	Ave. Suspended Solids	Ave. Total Solids
Primary effluent	117 mg/ℓ	80 mg/	310
Secondary effluent	27 mg/ℓ	22 mg/	250
Tap water	-	-	50

8. Surface vegetation - An initial assessment of the effect of vegetative transpiration on the operation of ET units was made. It was not intended to be a thorough study of this complex subject. Eleven units were evaluated over different time spans, several as constant water level lysimeters for the measurement of evaporation rate and others at constant loading rate to assess the effect of summer drought, winter freezing and year-round performance. Two units each were planted with Kentucky bluegrass, pfitzer (Juniper) bush, cottonwood (Populus candicans) sapling and Lombardy poplar (Populus nigra italica). In each case one unit was studied at a constant level of 22.9 cm (9 inches) below surface and one unit with constant loading, 16.3 mm/day (0.04 gal/day/ft^2). The other three units were planted with alfalfa, pussy willow (Salix discolor) and salt cedar (Tamarak). These units were observed under both loading conditions at different time intervals.

MECHANICAL EVAPORATION UNITS

The mechanical evaporation units were a development of the concept of designing a device that would provide a maximum of evaporative surface in a small vertically-projected area, utilize the energy of ambient air, be relatively maintenance free and have a low commercial energy requirement. Two types of units were tested: the Rotating Disk Evaporator (RDE) and Concentric Cylinder Evaporator (CCE) units. Schematic drawings of the units are shown in Figures 15 and 16. Photographs of the units were presented in Section 1.

The RDE and CCE units were fabricated to be identical except for the evaporation surfaces. The materials of construction were selected for durability and ease of fabrication. The wastewater reservoir was made from a 208 liter (55 gallon) drum cut

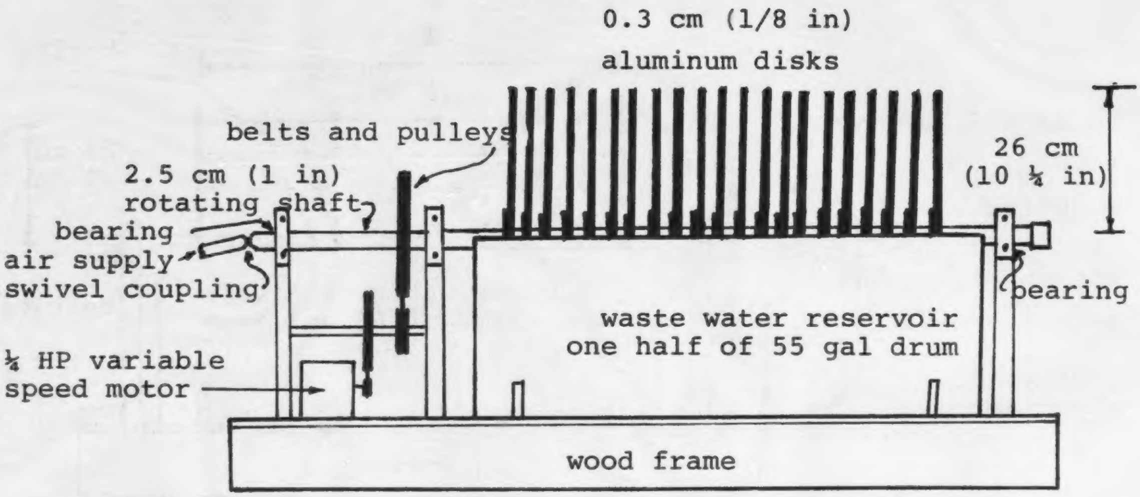

0.3 cm (1/8 in)
aluminum disks
belts and pulleys
2.5 cm (1 in)
rotating shaft
bearing
air supply
swivel coupling
26 cm
(10 ¼ in)
bearing
waste water reservoir
one half of 55 gal drum
¼ HP variable
speed motor
wood frame

Figure 15. Drawing of rotating disk evaporator.

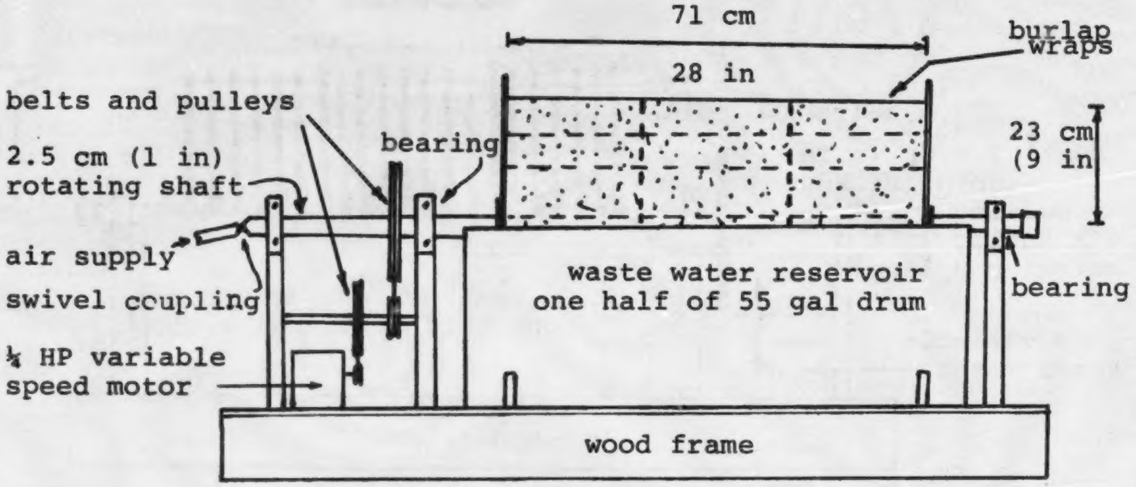

71 cm
28 in
burlap wraps
belts and pulleys
bearing
2.5 cm (1 in) rotating shaft
23 cm (9 in
air supply
swivel coupling
waste water reservoir one half of 55 gal drum
bearing
¼ HP variable speed motor
wood frame

Figure 16. Drawing of concentric cylinder evaporator.

lengthwise. An adjustable hook gage was bolted to the inside of the reservoir so that evaporated water volumes could be easily accounted. The support structure was fabricated from aluminum angle and channel sections. The center shaft of the rotating section was one inch (2.5 cm) diameter hollow T6064 aluminum pipe. The disks for the main test unit were cut from 1/8 inch (0.3 cm) T6064 aluminum sheet. The shaft collars, sheaves and sealed ball bearing pillow blocks were made of iron. The motor was an AC-DC universal type rated at 0.5 amps and supplied with rheostat control and reduction gearing. The unit shaft rotational speed was further reduced by use of a V-belt drive mechanism. Shaft rotational speeds could be set between 0.35 and 5 rpm. The fractional depth of wetting of the disks or cylinder could be set between 0.0 and 0.9. The CCE unit was identical except that the cylinder was constructed with aluminum disk end pieces to which three wraps of burlap cloth were attached. The diameter of the three cylinders were 15, 30, and 46 cm (6, 12, and 18 inches). Compressed air entered through drilled holes in the hollow center shaft and moved outward through the wetted cloth wraps. The compressed air was unsaturated upon entering and nearly saturated when leaving the outer cylinder wrap. Temperatures of the entering air and the water bath were recorded as well as compressed air pressure at the unit and air flow rate.

The method of operation of the units was to set a value for each of the machine variables and to fill the reservoir with wastewater to the level of the point of the hook gage. The unit was operated for a recorded period of time, usually two to twenty-four hours. The time period of a run was selected to be long enough so that several liters of wastewater was evaporated. In this way the inaccuracies of reading a hook gage were held within one percent. At the end of each run the unit was stopped and the amount of water evaporated was determined from the amount of wastewater required to bring the level back up to the point on the hook gage.

Two types of studies were made with each unit. Ambient air data was determined while the units were operated on the roof of the Engineering Center. This provided data under conditions that would be similar to those of a prototype unit. A small weather station was set up near the unit where continuously recorded data for ambient air temperature, pressure, relative humidity, wind speed, and solar radiation were taken. Standard class A pan evaporation and rainfall amounts were also measured.

For the study of some of the machine variables, it was found that more precision could be accomplished by moving the unit into the hydraulics laboratory where constant air temperatures and relative humidity existed. A plywood wind tunnel utilizing a fan was constructed for the laboratory studies so that wind speed could be accurately controlled, measured and reproduced.

For some of the studies of machine variables for the RDE unit, such as disk spacing or disk type, a reservoir was fabricated with water tight dividers and multiple hook gages so that comparative evaporation data for several values of the design parameters could be taken simultaneously with identical conditions for temperature, wind speed and relative humidity.

Series and Purpose of Tests

Rotating Disk Evaporator--

Three major parameters are involved in the equation describing the operation of the RDE unit: wind speed, humidity deficit and solar radiation. These parameters were evaluated separately and in combination. Since freezing weather requires special considerations for the sizing of the unit and storage vault, this parameter was also studied. Optimization of the design of a unit was approached with a series of tests involving each of the machine variables. The experimental methods and conditions were as follows:

1. Wind speed - Two types of testing were used to establish the wind speed function. The unit was placed in the plywood wind tunnel in the laboratory. Under conditions of constant temperature and relative humidity, measurements of evaporation rate were made for different wind speeds by adjusting the speed of the fan in the tunnel with a voltage regulator. The equation developed under the controlled laboratory conditions was compared to the results obtained with ambient air flow when the unit was operated outdoors. Ambient measurements were made on the roof of the University of Colorado Engineering Center, with and without the use of the wind tunnel. Wind speed measurements were made with a three-cup anemometer.

2. Wind direction - Using the laboratory wind tunnel conditions the RDE unit was tested at four different wind angles ranging from perpendicular to parallel to the rotating shaft. Evaporation measurements were made to establish the effect of wind direction.

3. Solar radiation - The contribution of solar radiation was established under ambient conditions by using a reservoir divided into two sections. One-half of the disks were shaded, using a wooden cover well above the disks so as not to affect wind movement. The evaporation rate of each group of disks was measured and the

difference was correlated with solar radiation measurements of the on-site pyranograph.

4. Humidity deficit - The degree of undersaturation of the air in contact with the evaporation surface is a major factor in the evaporation process. The function of this parameter was established from analysis of operational data recorded under different weather conditions during the winter and summer periods of outdoor operation. The average humidity deficit for each operational period was established from recorded temperature and relative humidity charts from the meteorograph located near the unit. Using a psychrometric chart, the average adiabatic humidity deficiency was calculated for each test condition.

5. Freezing conditions - An important consideration in the planning of a total evaporation system for year-round application is the period of the year when freezing conditions will prevent the use of an RDE unit or will require modification and commercial energy to prevent freezing. A brief study was made to determine the minimum temperature that would allow the unit to function. This was done under ambient winter conditions. When freezing occurred, a 3000 watt electric immersion heater was used in the reservoir of the unit. Electrical power requirements were measured with a meter and correlated with reservoir temperature, air temperature and evaporation rate.

6. Machine variables - The design of an RDE unit requires the optimization of mechanical components. The RDE unit was constructed in such a way that several machine adjustments could be made so that the relationship between evaporation rate and machine variables could be studied. This was done under both ambient and laboratory wind tunnel conditions. One variable was studied at a time, while keeping other parameters fixed. Evaporation rate was measured for different settings for each component variable. Those evaluated were:

    a. Rotational speed. A variable speed drive on the shaft motor allowed for rotational speeds of 0.3 to 5 rpm. The study was made in the laboratory to provide constant conditions for each setting.

    b. Submergence. By adjusting the hook gage in the reservoir, the depth of wetting of the rotating disks could be varied from zero to 0.9 of the full radius, measured from the outside edge. A reservoir with dividers was used so that five different submergence values could be studied simultaneously.

c. Disk spacing. The disks were adjustable on the shaft so that the spacing between disks could be varied from 1.27 to 7.62 cm (½ to 3 inches). The divided reservoir was used and several disk spacings were evaluated at the same time to determine evaporation rate per wetted disk area.

d. Disk color and material. Aluminum, plain plywood, plywood painted white, black plywood and white styrofoam disks all of 51 cm (20.5 inches) diameter were tested at the same time with the five section reservoir to study the effect of color and type of material used in the disks on the evaporation rate. The study was made under ambient conditions in bright sunlight.

e. Disk diameter. In order to utilize the results of the test unit for prediction of full scale prototype units, a larger three section reservoir was constructed and disks of three diameters were evaluated simultaneously. The disks were fabricated from plywood and had diameters of 0.51, 0.92 and 1.21 m (20.5 in., 3 ft and 4 ft).

7. Potential health hazard - The possibility of wind drift of water droplets from the units was evaluated in the laboratory by placing culture dishes directly upwind and downwind from the units at distances of 0.15, 1.5 and 3 m (0.5, 5 and 10 ft). The dishes contained coliform bacteria test media and milipore filters. The unit was operated for two hours and then the dishes were removed, incubated and tested for coliform bacteria in accordance with Standard Methods, 13th Ed. (1975).

Concentric Cylinder Evaporator--

The operational parameters of the CCE unit were quite similar to those of the RDE except that the mass flow and humidity deficit of the compressed air were the major factors controlling evaporation rate. The experimental methods and conditions were as follows:

1. Mass flow rate and ΔH - The compressed air entering the unit was controlled with a valve and had pressure gages at each end of the inlet line. The pressure drop through the inlet line was used to determine the flow rate. The relationship between flow rate and pressure drop was calibrated with a precalibrated rotometer and checked with a volume displacement technique. Evaporation rate was measured by use of a hook gage in the liquid reservoir in a manner similar to that with the RDE unit. The humidity deficit was determined from a

psychrometric chart. A thermometer was fixed into the air inflow line and a tee was placed in the line so that wet and dry bulb temperatures of the compressed air could be measured for each experimental test using an electronically aspirated Bendix psychron instrument.

2. Wind speed - The CCE unit was tested in the laboratory wind tunnel and under ambient conditions on the roof of the engineering building. The velocity of the air passing over the outside of the drum was measured with a three-cup anemometer in a manner similar to that with the RDE unit.

3. Solar radiation - The effect of solar radiation was measured from tests in which the unit was operated in the sunlight for a period during the middle of the day and then under shaded conditions for another period of nearly identical ambient parameters. Sunlight intensity was measured with a recording pyranograph.

4. Machine variables - Only three machine variables were evaluated: compressed air mass flow rate, rotational speed of the drum and submergence of the drum. The compressed air mass flow rate measurements have been discussed. The methods of making variations in rotational speed and cylinder submergence were identical to those of the RDE unit for rotational speed and disk submergence.

WEATHER MEASUREMENTS

For all outside field investigations, the temperature, relative humidity and barometric pressure were measured using a Weather Measure Corp. Model M701 meteorograph. The temperature, relative humidity, and barometric pressure were simultaneously recorded on a seven-day chart mounted on a clock driven drum. The meteorograph utilized a bimetallic strip for temperature measurement, a human hair bundle for relative humidity measurements, and an aneroid for pressure measurements.

Solar and diffuse sky short-wave radiation were measured and recorded using a Weather Measure Corp. Model R401 mechanical pyranograph. The instrument utilized bimetallic strips to determine solar and diffuse sky short-wave radiation on a horizontal plane. Radiation was recorded on a seven-day chart mounted on a clock driven drum.

The rainfall was recorded using a Weather Measure Corp. Model P501-I remote recording rain gage which was connected to a Model P521 event recorder. The rain gage was of the tipping bucket type. Each bucket tip sent an electric impulse to the event recorder which recorded the impulse on a seven-day chart mounted on a clock driven drum.

Wind was measured using a Weather Measure Corp. Model W164-B/M contact anemometer. The three-cup anemometer measured kilometers of wind at a height of 40 cm (15 in.). The instrument was calibrated in the low velocity wind tunnel at the NOAA Boulder test facility.

Pan evaporation was measured using a standard U.S. Weather Bureau class A pan. The pan was of stainless steel construction, 122 cm (4 ft) in diameter and 25.4 cm (10 in.) deep. The pan was placed on a wood frame to allow air to circulate beneath it. A hook gage placed in a stilling well was used to measure the drop in the water surface over a definite time period. The screw-type hook gage had a precision of 0.025 mm (0.001 in.). Pan evaporation was computed as the difference between observed levels minus the measured precipitation.

The meteorograph and event recorder were housed in a screened instrument shelter at a height of 1.2 m (4 ft). The rain gage was placed through the roof of the shelter. The pyranograph was attached to the roof of the shelter. The evaporation pan and anemometer were placed near the instrument shelter at the ground level.

Mean values of temperature, relative humidity and solar radiation were determined by integrating the area under the line made by the trace on the recording chart. The mean wind speed was determined by dividing the total kilometers of wind during a data period by the time interval. Only the total depth of rainfall over a data period was required and this could be read directly from the event recorder's chart. The mean humidity deficit over a data period was determined using the mean temperature of the air, the mean relative humidity, and a psychrometric chart corrected for the altitude of Boulder, Colorado; barometric pressure of 84 kPa (0.83 atm) Hg.

In the portion of the report dealing with design and cost consideration, meteorologic data from NOAA was used for interpretation of applicability to Boulder and other locations. The individual readings taken at the research location correlated closely with the NOAA readings for the same period.

SECTION 7

RESULTS

The testing of the ET lysimeters and mechanical units was conducted at the Engineering Center of the Boulder Campus of the University of Colorado.

Twenty lysimeters were constructed in the fall of 1975. After initial equilibration, testing was begun in January of 1976. Nine additional lysimeters were added in September of 1976. Testing was continued through September of 1977. The lysimeters were buried in the earth in an area adjacent to the southeast corner of the building. The units were in an area protected by a concrete wall. The building and the wall were such a distance as to provide no restrictions to sunshine or rainfall and relatively little effect on air movement.

The two mechanical evaporation units were fabricated in the laboratory shop in the winter of 1975 and spring of 1976. Testing was initiated in June of 1976 and continued until August of 1977. The ambient testing of the mechanical units was conducted on the roof of the three story civil engineering wing of the building. This provided an essentially unobstructed location. The weather station used to gather ambient air readings was at the same location. The testing of the units under controlled windspeed and temperature conditions was done in the fluid mechanics laboratory.

The test site is located in a semi-arid region of the U.S. in the rain shield of the front range of the Rocky Mountains. Boulder is located at an elevation of 1700 meters (5600 feet) above sea level, immediately adjacent to the eastern edge of the mountains. The monthly weather summary for the test period and the normal values are shown in Table 6. Boulder has a normal average precipitation rate of 412 mm (18.57 inches) per year, snowfall of 2057 mm (81 inches) and total evaporation of approximately 1500 mm (60 inches). The study period was characterized by drought conditions with moisture about twenty percent below normal and snowfall at approximately one-half of normal.

ET LYSIMETER DATA ANALYSIS

The first series of tests with parametric variations was initiated in January 1976. The loading patterns were changed at

TABLE 6. WEATHER SUMMARY FOR THE TEST AREA

	Mean Temp ^{o}F			Max. Temp of		Min. Temp of		Days with Min. Temp Below 32^{o}F		Cloud Cover Days			Moisture in		
	1976	1977	Norm	1976	1977	1976	1977	1976	1977	Clear 1976	Partly 1976	Cloudy 1976	1976	1977	Norm
January	32.5	28.2	32.7	65	56	-2	-10	25	31	13	17	1	0.42	0.08	0.72
February	41.4	39.0	34.7	65	68	-1	12	11	22	7	20	2	0.34	0.45	0.83
March	38.5	39.5	39.4	69	69	0	14	24	25	10	19	2	1.19	0.53	1.75
April	49.2	49.5	48.7	74	78	26	8	2	7	5	21	4	1.99	3.32	2.75
May	56.4	56.9	57.4	83	86	31	33	1	0	8	18	5	2.14	0.93	3.36
June	66.3	71.2	67.5	92	95	43	47	0	0	12	18	0	1.25	0.66	1.89
July	73.2		73.6	99	96	52	50	0	0	7	24	0	1.62	3.24	1.41
August	69.7		72.1	92	87	48	48	0	0	8	22	1	1.43	2.38	1.64
September	60.8		64.4	91	92	32	31	0	1	11	14	5	2.73	0.16	1.25
October	49.4		53.8	80		18		15		14	16	1	1.02		1.39
November	39.3		41.4	70		-7		20		8	18	1	0.21		0.96
December	36.6		35.8	63		1		23		16	14	1	0.32		0.62
Mean	51.1		51.7	65		37									
Total								121		119	221	16	14.66		18.57

(Continued)

TABLE 6 (Continued)

	Snow in			Pan Evap. in		Relative Humidity	Wind, mph	ΔH gm/kg	Sunlight ly/hr
	1976	1977	Norm	1976	1977				
January	8.3	4.0	10.9	2.36*	2.36*	51	9.6	0.29	10
February	6.2	7.4	10.8	3.78	2.36*	56	9.7	0.71	12
March	4.5	5.9	17.3	4.84	3.77	55	10.3	1.00	18
April	0	12.6	14.3	5.24	6.29	50	10.6	1.43	22
May	0	0	2.8	5.65	9.76	52	9.8	2.14	25
June	0	0	0.1	10.65	11.56	58	9.3	2.21	25
July	0	0	0	10.32	10.23	53	8.7	2.79	28
August	0	0	0	8.38	9.45	53	8.5	2.71	23
September	0	0	1.0	5.01		55	8.4	2.29	18
October	2.1		4.3	4.13		54	8.3	1.86	15
November	1.0		11.5	2.36*		54	8.9	1.00	10
December	7.0		8.0	2.48*		54	9.3	0.86	7
Mean									
Total	41.0		81.0	65.2					

*Estimated from lysimeter studies.

specific intervals during the course of the study in order to investigate a wide range of conditions. The loading conditions are shown in Table 7. It can be noted that some of the units were utilized for several different parametric tests. This is indicated with the letter designation (a) through (f) with the unit number. Tests on units with the letter (a) were initiated at the beginning of the study. The loading rates of three of the units were changed on July 14, 1976. These units were designated with the letter (b) at that point. Eight additional units were added on October 1, 1977. For the new lysimeter, and for the existing units where the loading rate was changed, designation with the letter (c) is used. Further variations were made on January 1, 1977 and designated with (d). During the last two months of the testing, short term tests were made with transpiration rate measurements of cottonwood and poplar trees using the unit designated with (e). These tests were initiated on August 1, 1977. In order to assess evaporation rate differences due to the type of feed water involved, primary effluent, secondary effluent and tap water evaporation rates were measured in the units labeled (f), commencing on September 1, 1977.

ET units respond rather slowly to changes in loading variables. For some of the variables studied, it was necessary to observe the units for more than the full year cycle. For a few units, loadings were unchanged over the complete study period. Other parameters could be evaluated in a shorter period of time and loading parameters were changed on a more frequent interval in order to study a wider variety of conditions. In all, fifty-seven different test conditions were evaluated.

The two major types of loading methods are indicated in the table. Under one type of loading condition, a constant amount of wastewater was added each day, such as 1.6 mm/day (0.04 gallons per square foot of surface area) and the water level within the unit was allowed to be variable, changing with the evaporative conditions present. The other type of loading involved feeding a variable amount of wastewater each day in such a way that the gravity water level within the lysimeter remained nearly constant. The first type of loading generally requires long term testing and water level changes within the lysimeter are observed through different seasons of the year. The maximum loading that would allow for year round operation without overflowing was established from units operated in this manner. The second type of loading allows for continuous evaporation rate measurements. The amount of water added to maintain a constant level represents the amount evaporated and can be correlated to the parameters being studied.

TABLE 7. LYSIMETER STUDY CONDITIONS

Lysimeter Number	Study Period	Loading Rate mm/day	Gravity H_2O Depth from Surface	Special Conditions
1a	1-1-76/7-14-76	1.6 (0.04 gpd/ft^2)	variable	Alfalfa planted on surface
1b	7-14-76/10-1-76	variable	0.58 m (23 in)	Alfalfa planted on surface
1c	10-1-76/8-30-77	variable	0.23 m (9 in)	Alfalfa planted on surface
2a	1-1-76/8-30-77	1.6 (0.04 gpd/ft^2)	variable	*
3a	1-1-76/8-30-77	3.2 (0.08 gpd/ft^2)	variable	*
4a	1-1-76/10-1-76	0.4 (0.01 gpd/ft^2)	variable	*
4c	10-1-76/8-30-77	0.8 (0.02 gpd/ft^2)	variable	*
4f	9-1-77/9-22-77	variable	0.23 m (9 in)	Secondary effluent feed @ 20°C (68°F)
5a	1-1-76/8-30-77	1.6 (0.04 gpd/ft^2)	variable	Primary effluent feed @ 50°C (122°F)
5f	9-1-77/9-22-77	variable	0.23 m (9 in)	Tap water feed at 20°C (68°F)
6a	1-1-76/8-30-77	1.6 (0.04 gpd/ft^2)	variable	Opaque cover excludes sunlight & precip.
7a	1-1-76/8-1-77	variable	0.58 m (23 in)	*
7e	8-1-77/9-22-77	1.6 (0.04 gpd/ft^2)	variable	Cottonwood tree planted
8a	1-1-76/10-1-76	8.0 (0.20 gpd/ft^2)	variable	Has gutter to measure runoff
8c	10-1-76/1-1-77	4.0 (0.10 gpd/ft^2)	variable	*
8d	1-1-77/8-30-77	1.2 (0.03 gpd/ft^2)	variable	*
8f	9-1-77/9-22-77	variable	0.23 m (9 in)	Primary effluent feed @ 20°C (68°F)
9a	1-1-76/8-30-77	1.6 (0.04 gpd/ft^2)	variable	Clear plastic cover excludes precip.
10a	1-1-76/1-1-77	1.6 (0.04 gpd/ft^2)	variable	Has gutter to measure runoff, surface slope 1:2, 2" top soil
10d	2-1-77/8-30-77	2.0 (0.05 gpd/ft^2)	variable	Surface slope changed to 1:6, top soil removed
11a	1-1-76/8-30-77	1.6 (0.04 gpd/ft^2)	variable	Sod grass cover, has gutter to measure runoff
12a	1-1-76/8-1-77	variable	0.46 m (18 in)	*
12e	8-1-77/9-22-77	variable	0.23 m (9 in)	Cottonwood tree planted
13a	3-1-76/10-1-76	1.6 (0.04 gpd/ft^2)	variable	Special finer ET sand, Golden Sand w/all larger than 100 mesh removed

(Continued)

TABLE 7 (Continued)

Lysimeter Number	Study Period	Loading Rate mm/day	Gravity H_2O Depth from Surface	Special Conditions
13c	10-1-76/1-1-77	variable	0.23 m (9 in)	Special finer ET sand, Golden Sand w/all larger than 100 mesh removed
13d	1-1-77/8-30-77	variable	0.58 m (23 in)	Special finer ET sand, Golden Sand w/all larger than 100 mesh removed
14a	1-1-76/7-14-76	1.6 (0.04 gpd/ft^2)	variable	Has gutter to measure runoff, surface slope flat
14b	7-14-76/10-1-76	variable	0.58 m (23 in)	Clear plastic cover precludes sunlight & precipitation
14c	10-1-76/8-30-77	variable	0.23 m (9 in)	Clear plastic cover precludes sunlight & precipitation
15a	1-1-76/10-1-76	6.4 (0.16 gpd/ft^2)	variable	*
15c	10-1-76/8-30-77	2.4 (0.06 gpd/ft^2)	variable	*
16a	1-1-76/10-1-76	variable	0.23 m (9 in)	*
16c	10-1-76/8-30-77	variable	0.23 m (9 in)	Sod grass cover
17a	3-1-76/10-1-76	1.6 (0.04 gpd/ft^2)	variable	Special coarse ET sand, Golden Sand w/all smaller than 100 mesh removed
17c	10-1-76/1-1-77	variable	0.23 m (9 in)	Special coarse ET sand, Golden Sand w/all smaller than 100 mesh removed
17d	1-1-77/8-30-77	variable	0.58 m (23 in)	Special coarse sand sand, Golden Sand w/all smaller than 100 mesh removed
18a	1-1-76/10-1-76	1.6 (0.04 gpd/ft^2)	variable	Has gutter to measure runoff
18c	10-1-76/8-1-77	variable	0.23 m (9 in)	Pussy willow planted
18e	8-1-77/9-22-77	variable	0.23 m (9 in)	Poplar tree planted
19a	1-1-76/7-14-76	0.0 (0.00 gpd/ft^2)	variable	Has gutter to measure runoff
19b	7-14-76/10-1-76	variable	0.58 m (23 in)	Opaque cover added, precludes sunlight & precipitation
19c	10-1-76/8-30-77	variable	0.23 m (9 in)	*
20a	1-1-76/8-30-77	variable	0 mm (full)	Has gutter to measure runoff

(Continued)

TABLE 7. (Continued)

Lysimeter Number	Study Period	Loading Rate mm/day	Gravity H_2) Depth from Surface	Special Conditions
21c	10-1-76/8-30-77	0.0 (0.00 gpd/ft^2)	variable	*
21f	9-1-77/9-22-77	variable	0.58 m (23 in)	Secondary effluent feed, 20°C (68°F)
22c	10-9-76/8-1-77	variable	0.32 m (15 in)	*
22d	8-1-77/9-22-77	1.6 (0.04 gpd/ft^2)	variable	Poplar tree planted
23c	10-1-76/8-1-77	variable	0.18 m (7 in)	*
23e	8-1-77/9-22-77	variable	0.23 m (9 in)	Poplar tree planted
24c	10-1-76/1-1-77	variable	0.23 m (9 in)	Pfitzer planted
24d	1-1-77/9-22-77	1.6 (0.02 gpd/ft^2)	variable	Pfitzer planted
25c	10-1-76/9-1-77	1.6 (0.02 gpd/ft^2)	variable	Surface slope flat
25f	9-1-77/9-22-77	variable	0.58 m (23 in)	Primary effluent feed @ 20°C (68°F)
26c	10-1-76/9-22-77	variable	0.23 m (9 in)	Pfitzer planted
27c	10-1-76/9-22-77	variable	0.23 m (9 in)	Salt cedar tree planted
28c	10-1-76/9-1-77	variable	0.23 m (9 in)	*
28f	9-1-77/9-22-77	variable	0.58 m (23 in)	Tap water feed @ 20°C (68°F)
pan (29)	1-1-76/9-22-77	variable	pointer	Filled each day to point gage

*Standard lysimeter conditions - All units had Golden ET sand with bare surface at a slope of 1:6 and primary effluent feed water at a temperature of 30°-37°C except as noted under special conditions.

Loading Parameter

Ten different constant loading rates were used during several periods of the study to provide an understanding of how the units functioned and to establish the maximum year round loading for the weather conditions that existed. The objective of this portion of the research was to correlate performance of ET beds with weather variables in order to establish parameters for design for other locations and weather conditions. The ten loadings utilized were:

Loading mm/d	Loading gal/day.ft^2	Lysimeter No.	Length of Testing
0	0.00	19a & 21c	20 months
0.4	0.01	4a	8 "
0.8	0.02	4c	12 "
1.2	0.03	8d	8 "
1.6	0.04	2a	20 "
2.0	0.05	10d	7 "
2.4	0.06	15c	12 "
3.2	0.08	3a	20 "
4.0	0.10	8c	4 "
6.4	0.16	15a	8 "
8.0	0.20	8a	8 "

A plot of the results of one of the long term test units (#2a, 1.6 mm/d or 0.04 gpd/ft^2) is shown in Figure 17. The lower portion of the figure shows the loading due to rainfall and wastewater as well as the evaporation rate. Loadings and measurements were made each day. The data has been plotted on the basis of weekly averages in order to provide the detail necessary for understanding the functioning of the units. The upper portion of the figure shows the variation in depth of the gravity water surface for the unit over the twenty month test period.

The unit was constructed with moist ET sand delivered by a local supplier. It can be noted that in February and March of 1976 two snow storms provided loadings that were in excess of the evaporation rate and the unit began to fill with gravity water. In late April and May two large rainstorms caused rapid filling of the unit, almost to overflowing. During June, July and August, the high evaporation rate resulted in rapid drying of the sand and no gravity water was present, although the unit did contain capillary-held soil moisture. In the fall of 1976, when rainfall exceeded evaporation, the unit began to fill again. A large storm in April caused the unit to fill nearly to the top but it was possible to load the lysimeter in the normal fashion without causing overflowing. May of 1977 was an unusually dry month and the gravity water level disappeared and did not return for the remainder of the study. It was possible to load the unit

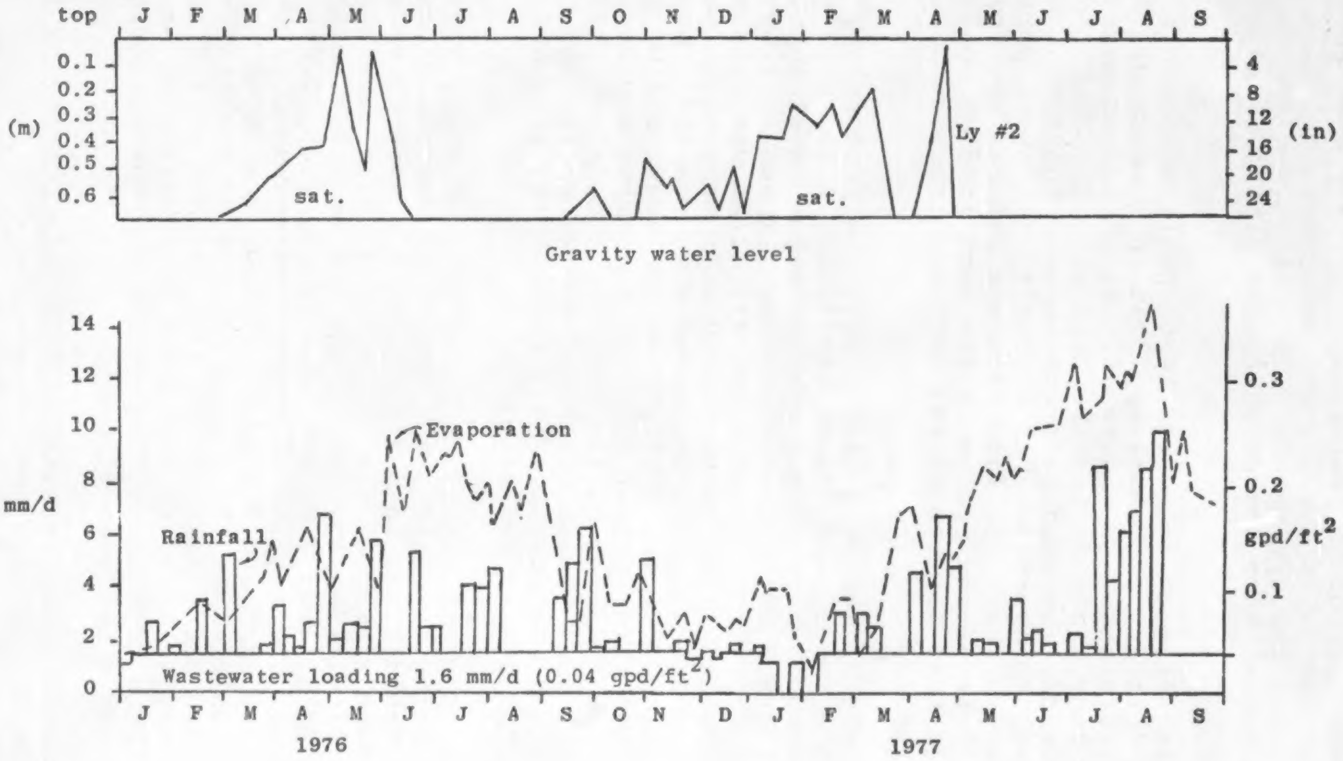


Figure 17. Effect of wastewater loading of 1.6 mm/d (0.04 gpd/ft^2) on lysimeter gravity water level.

without overflowing throughout the length of the study period. There was a brief period in January and February when the filler pipe was frozen and daily loading was not possible. This problem was due to the way the lysimeters were constructed and would not occur with an actual home system where the piping would be underground.

The loading diagram and water level profile for unit #3 with a sewage (primary effluent) application rate of 3.2 mm/day (0.08 gpd/ft^2) are shown in Figure 18. At this loading rate the unit was full many times during the test period. When the full condition occurred, the feed rate was reduced instead of permitting the unit to overflow. As a result, all those portions of the lower curve where the feed rate was reduced represent periods of failure of the system at the test loading condition. It can be noted that failure of the unit was frequent during the winter and spring.

The lysimeters that were tested with low feed rates, 0.00 mm/day, 0.4 mm/day and 0.8 mm/day (0.00, 0.01, 0.02 gpd/ft^2) did not fill enough to produce a gravity water level in the lysimeter during any portion of the study. These loading values are well below the critical value and all water was held as capillary pore water. The units tested with very high feed rates: 6.4 mm/d and 8.0 mm/d (0.16 and 0.20 gpd/ft^2), were full continuously throughout the test period and could not be loaded at the prescribed rate without overflowing during any season of the year. The unit loaded at 4.0 mm/d (0.10 gpd/ft^2), #15c, was operated for the four winter months of September through December. During that period the unit was full most of the time and could not be fed at the prescribed rate.

It became apparent after the first year of study that the appropriate loading for year round operation for the climatic conditions of Boulder was in the range of 1.6 mm/d (0.04 gpd/ft^2). During the second winter of the study three units were brought to a water level similar to that of the 1.6 mm/d lysimeter and were then loaded at 1.2, 2.0, 2.4 mm/d (0.03, 0.05, 0.06 gpd/ft^2) (#8d, 10d, 15c). The results of these loadings as well as from the 0.8 mm/d, 1.6 mm/d and 3.2 mm/d loadings are shown in Figure 19. It can be noted that #8d at 1.2 mm/d (0.03 gpd/ft^2) never completely filled and that #10d and #15c, loaded at 2.0 and 2.4 mm/d, respectively, filled to the point of overflowing several times during the winter and spring months and the prescribed loading rates could not be sustained.

Two conclusions can be reached from this portion of the study: (1) the appropriate maximum loading rate for the test conditions was 1.6 mm/d (0.04 gpd/ft^2) and (2) the units performed in a very similar manner and only through daily measurement was it possible to determine the point of maximum allowable loading. If observations could be made of field installed units

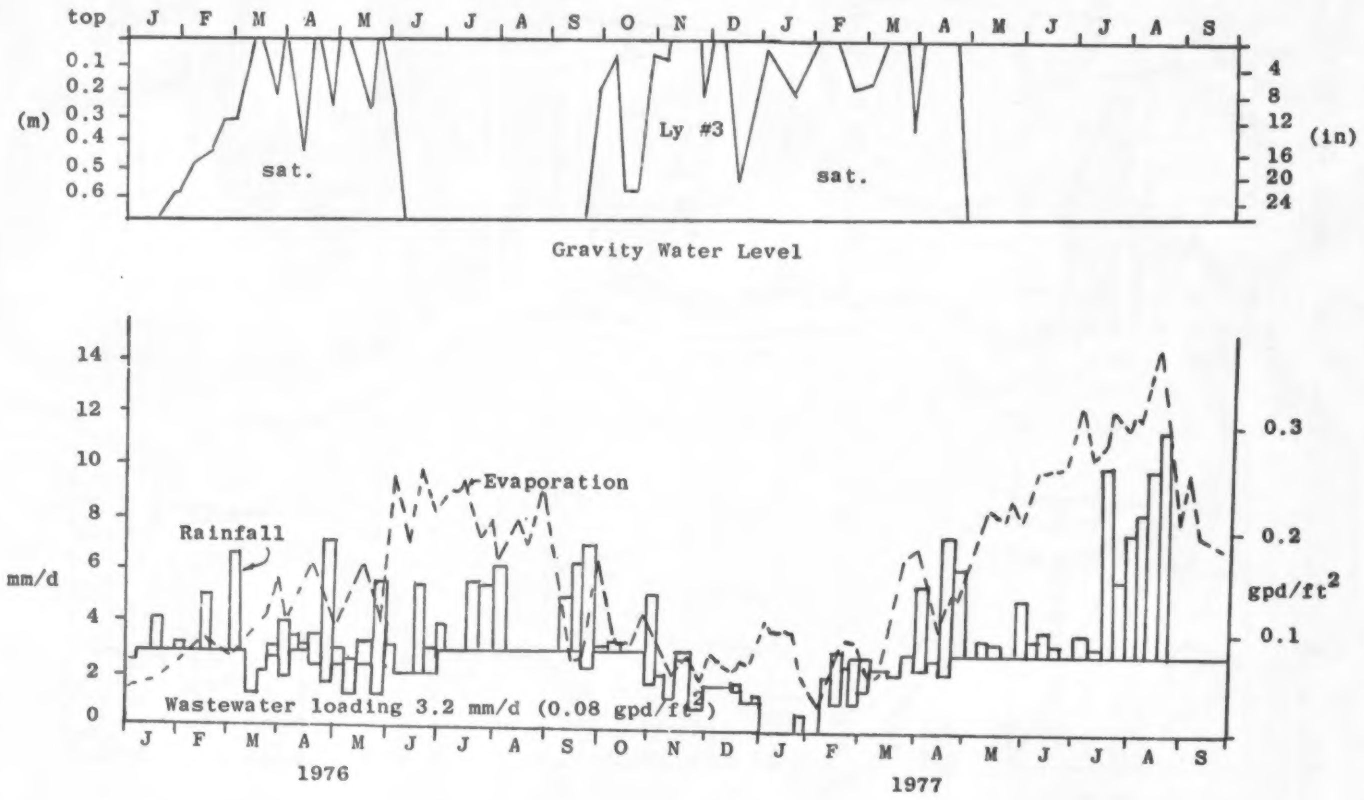


Figure 18. Effect of wastewater loading of 3.2 mm/d (0.08 gpd/ft^2) on lysimeter gravity water level.

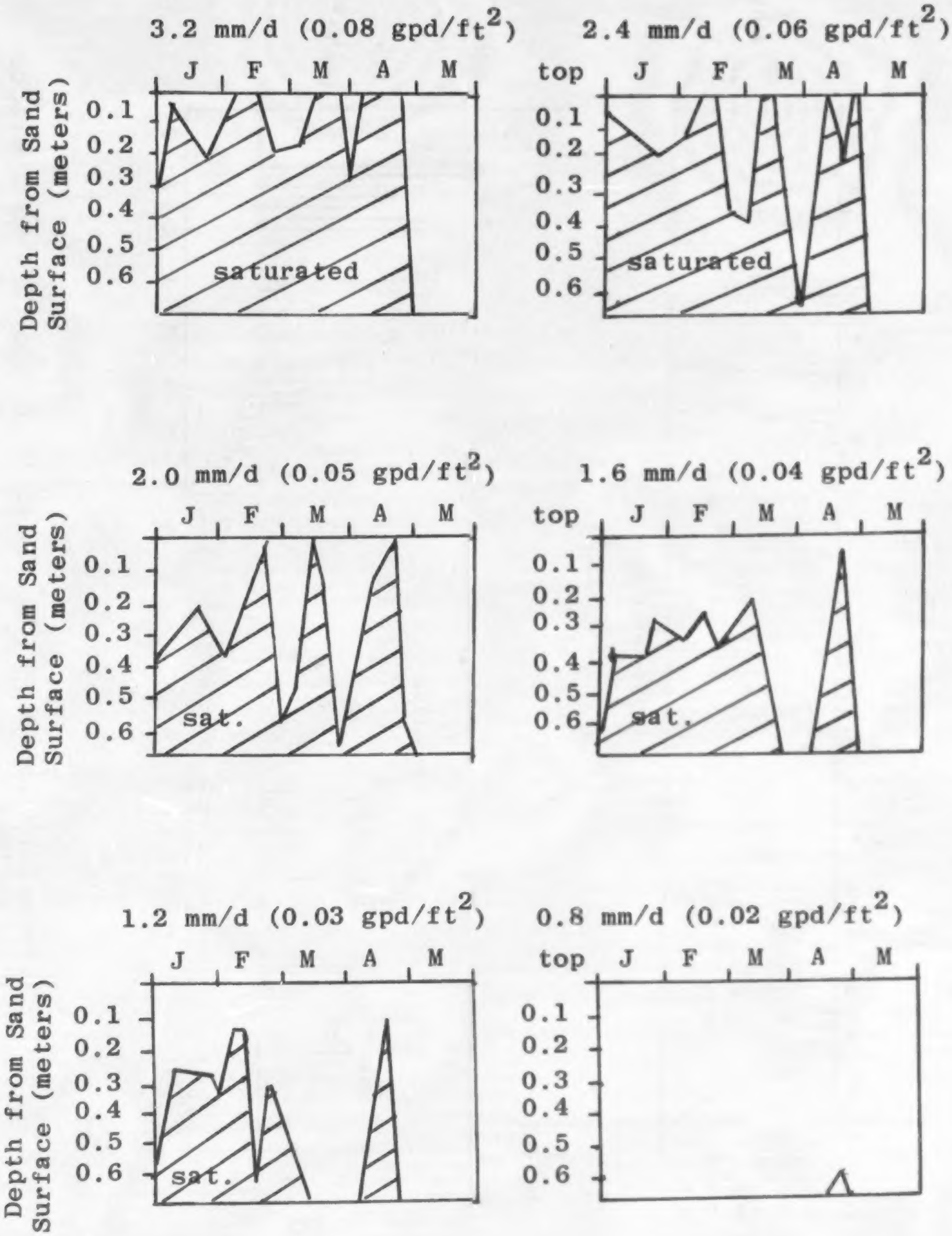


Figure 19. Gravity water level pattern during critical months for six loading conditions.

with loadings between 1.2 and 2.4 mm/d (0.03 and 0.06 gpd/ft^2), it would be very difficult to define differences in their performances by noting surface moisture conditions.

Depth of Gravity Water

A greater understanding of the performance of an ET bed can be gained from studies of evaporation rate as a function of gravity water depth in the bed. Six lysimeters operated at constant gravity water levels were used to establish this function. The test conditions are given below.

m	Inches	Fraction	Lysimeter #	Length of Testing
0	0	full	20a	20 months
0.17	7	1/4	23c	10 "
0.22	9	1/3	16a & 28c	20 "
0.37	15	~ 1/2	22c	10 "
0.44	18	2/3	12a	20 "
0.58	23	~ 1/7	7a	20 "

Total depth = 0.67 m, 27 inches

The evaporation rates for each month are shown graphically in Figure 20. The evaporation rate in each case was calculated as the sum of the sewage effluent added to the unit and the recorded rainfall. In Figure 21 the average evaporation rate corresponding to each gravity water level was calculated and plotted as a fraction of the evaporation rate measured from the class A pan at the site. The evaporation rate is reduced with the depth of gravity water because of the reduced moisture content at the surface of the sand bed. This has been illustrated in Figure 11. It has been shown in Figure 17 (ly #2) that a gravity water surface did not exist in the summer period and all water was held as interstitial capillary water. Under this condition, the evaporation rate would be even a lower fraction of the pan evaporation rate than the minimum value shown in Figure 21.

The average evaporation rate for the unit #2a that was loaded at 1.6 mm/day (0.04 gpd/ft^2) was calculated to be 62 percent of the measured evaporation of the unit maintained in the saturated condition (#20a), and 58 percent of the pan evaporation. Since the evaporation rate in the eight winter-spring months of October through May was about 73 percent of pan evaporation, the summer month rate was only about 25 percent of pan evaporation. From this it can be concluded that the moisture content of the unit fluctuates in such a manner that the actual evaporation rate from the unit is nearly constant throughout the year. The actual evaporation rate increases slightly in late May and June as the gravity water level decreases and disappears

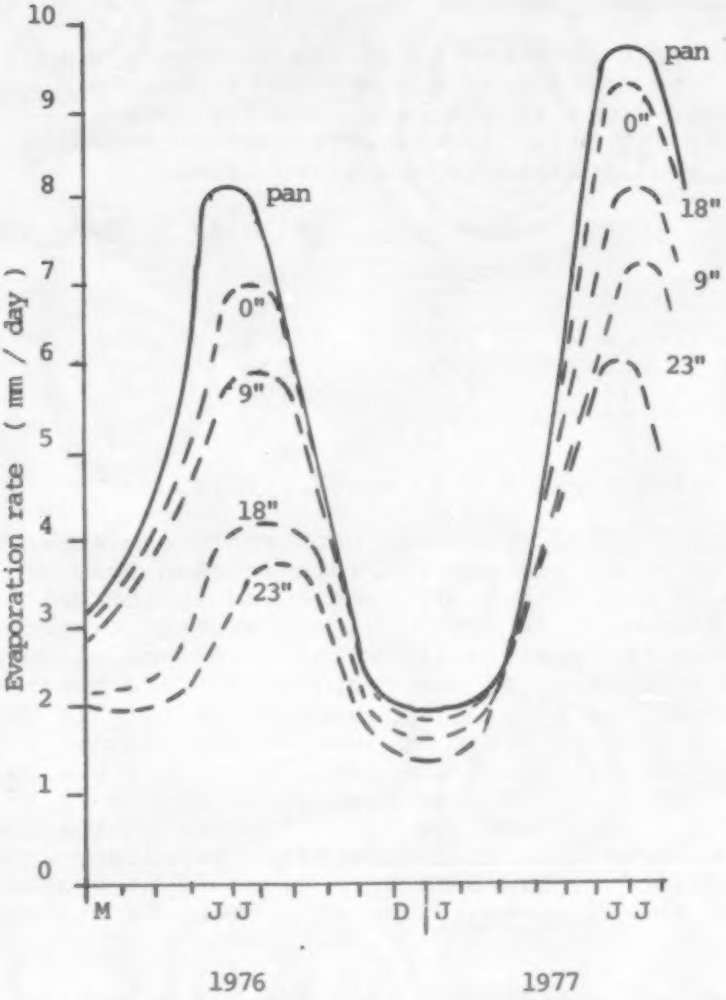


Figure 20. Monthly evaporation rate as a function of the depth of the gravity water surface in the lysimeter.

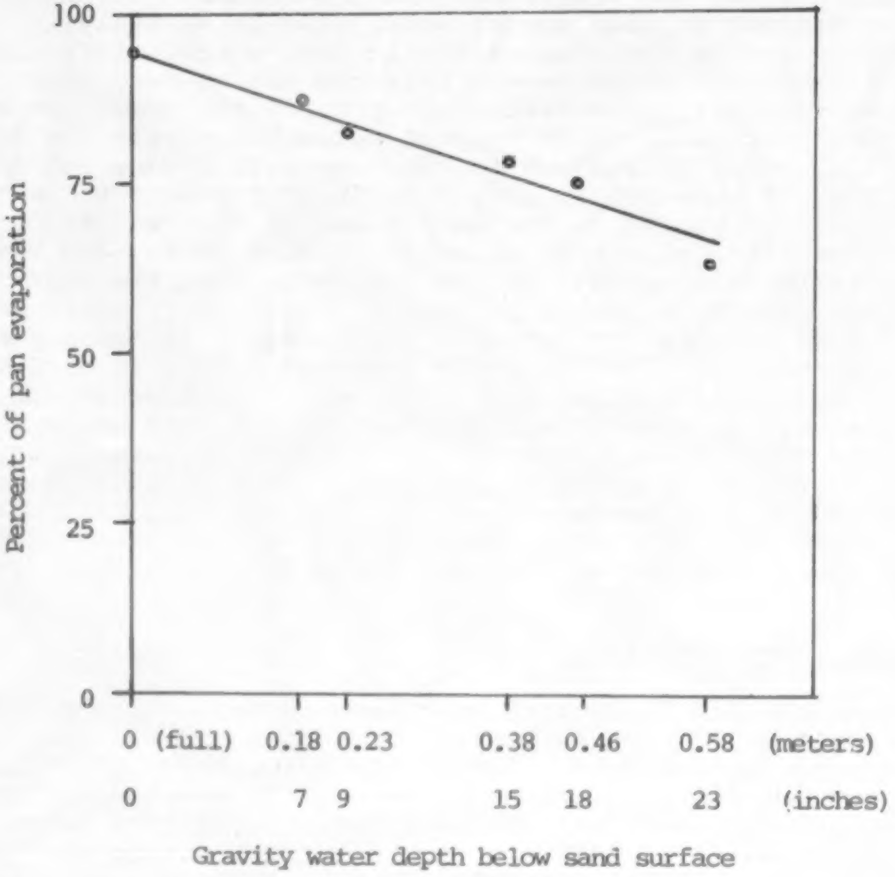


Figure 21. Lysimeter evaporation rate as a function of gravity water depth.

and is decreased slightly in the fall when the gravity water reappears, but it is much more constant over the year than the pan evaporation rate.

The high pan evaporation rates occurring at mid-summer, during the period when moisture content of the unit is low, have little effect on the functioning of the system. The ET units studied did not provide enough water storage capacity to hold the winter inflow for evaporation in the summer. Increasing the depth of the unit would necessitate the use of very small particle size materials (silts) to provide the necessary capillary rise potential. This type of media has a very low hydraulic conductivity and is subject to clogging with sewage solids. Therefore, ET beds should have a depth of 0.5 m to 0.7 m (20 in. to 30 in.) and should be designed based on the weather conditions during the critical months of December through May and not on yearly evaporation rates, nor on the basis that the unit acts as a storage reservoir during periods of low evaporation and has accelerated evaporation rates in the summer. It can be noted in Figure 17 that the lysimeter was near saturation in early October and remained that way until May. Non-discharging ET beds designed for year round application can only be used in locations where evaporation rate substantially exceeds precipitation during every month of the year. This consideration can be applied to combination ET-seepage systems to indicate that evaporation will provide a minimal contribution during those months where evaporation does not substantially exceed precipitation.

Sunlight and Rainfall Effects

Four covered lysimeters were used to evaluate the effect of rainfall and direct sunlight. The units had low open covers as pictured in Figure 14. Two of the units had clear plastic surfaces that prevented rainfall or snow from entering the unit but permitted direct sunlight to strike the ET sand surface. The clear plastic surface was replaced twice during the study period to ensure a maximum transmittance of sunlight. The other two units had opaque plywood covers that eliminated rain, snow and sunlight. The units were tested 1) in the constant loading mode at 1.6 mm/day (0.04 gpd/ft^2) and 2) at a constant gravity water level, 0.23 m (9 in) from the surface.

Unit	Cover	Loading	Period
14	clear	variable at 0.23 m	12 mo
19	opaque	variable at 0.23 m	12 mo
6a	clear	1.6 mm/d (0.04 gpd/ft^2)	20 mo
9a	opaque	1.6 mm/d (0.04 gpd/ft^2)	20 mo

The results of the variable loading units with the water level held at 0.23 m (9 in.) below the ET sand surface are shown in Figure 22. It can be noted that the opaque covered unit produced less evaporation, especially in the summer period when sunlight intensities were high. The average evaporation rate for the 12 months was 4.2 mm/d (0.105 gpd/ft^2) for the clear covered unit and 3.0 mm/d (0.075 gpd/ft^2) for the opaque unit. Direct sunlight was responsible for an average of twenty-nine percent of the annual evaporation rate with ranges from thirteen percent in the winter months of November, December and January to thirty-seven percent in June, July and August. The major portion of the evaporation at all times of the year resulted from the wind movement over the ET surface.

The evaporation rate from the clear covered unit (#14) was nearly the same as from the uncovered units held at the same water level (#16a, 28c on Figure 20). This is one indication that very little rainfall runoff occurred and that calculations of total monthly evaporation rates on the basis of wastewater loading plus precipitation are valid for this investigation.

The results for the covered units loaded continuously at 1.6 mm/d (0.04 gpd/ft^2) are shown in Figure 23. Superimposed on the upper graph is the water level pattern of the open unit (#2a) with the same loading. During the first nine months of testing, the results show the general pattern of the opaque covered unit to be similar to the open unit except for the absence of the rainfall spikes. The open unit received a slightly higher loading because of the rainfall but it also received direct sunlight. The clear covered unit received the lower loading without rainfall and received direct sunlight. The effect of direct sunlight is quite apparent in June and July when comparing the opaque covered unit with the others. The second year of the study produced a similar pattern except that, after the first summer, the clear plastic cover began to discolor and it was decided not to replace it. As a result, the performance became quite similar to that of the opaque unit.

Rainfall Runoff and Surface Slope

Seven of the lysimeters were equipped with small aluminum gutters around the circumference of the unit to collect runoff during precipitation events. The gutters drained into covered plastic containers and the collected water was measured volumetrically after each rainfall or snowmelt. The measurement of runoff was made for each storm during the first eight months of the study. Three different surface slopes were used: 26° (1:2), 9° (1:6), and 0° (flat). The 9° (1:6) slope was tested under three conditions: (1) with the ET soil near saturation at the time of rainfall, (2) with the ET soil undersaturated during rainfall, and (3) with a grass-sod growing on the surface. The results are shown in Figure 24. The curves rise sharply for precipitation of 25 mm (1 inch) but in general the runoff coefficient (volumetric ratio of runoff to precipitation) was less

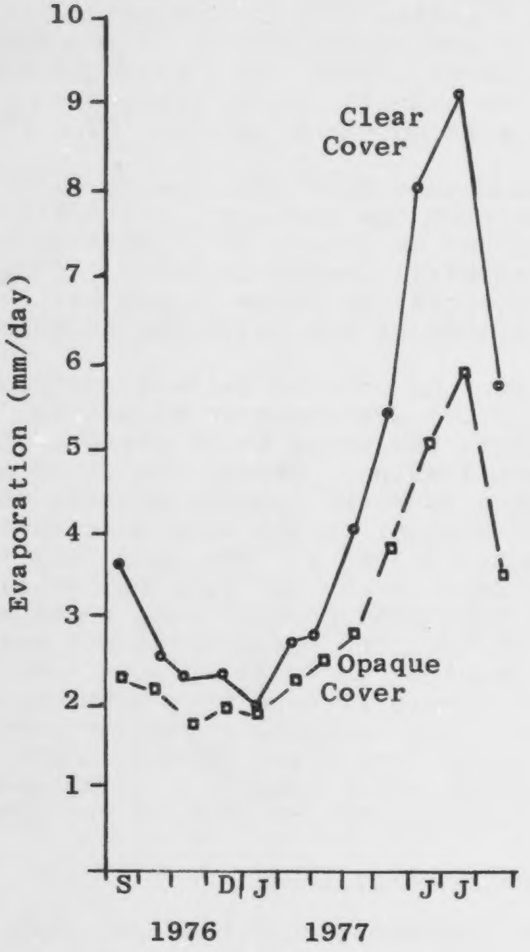


Figure 22. Monthly evaporation rate for clear and opaque covered lysimeters.

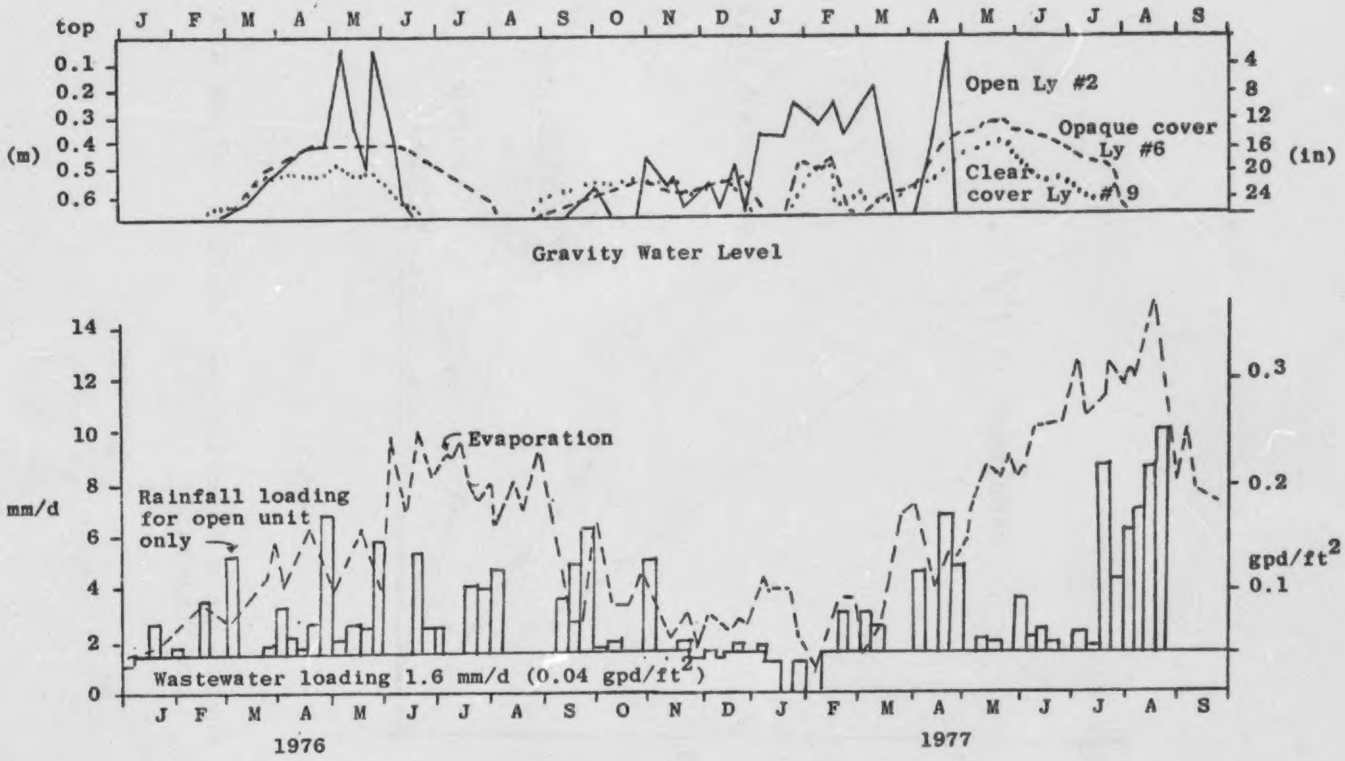


Figure 23. Effect of clear and opaque covers on lysimeter gravity water level.

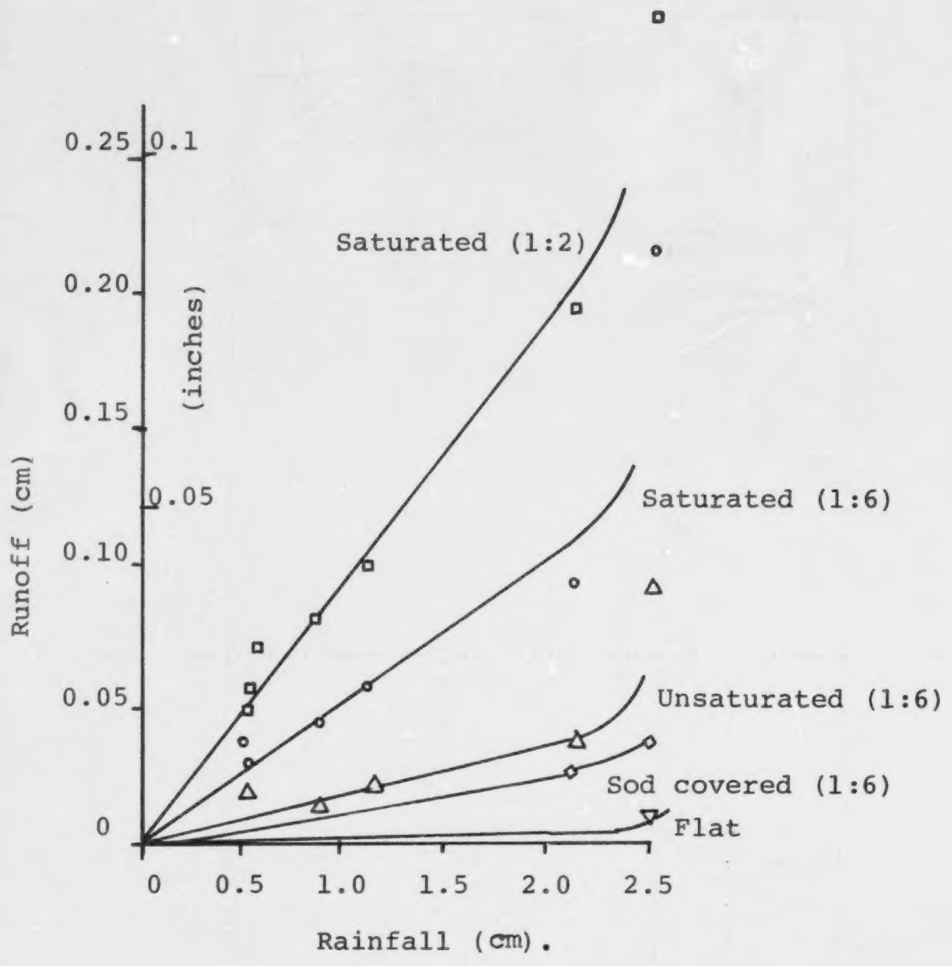


Figure 24. Runoff as a function of rainfall, slope and soil condition.

than 0.1 and was in the range of 0.02 for the bare, unsaturated ET sand surface. Although the units had a very small surface area for making runoff studies, the results show that runoff is a minimal fraction of precipitation. The assumption that all precipitation entered the beds and became a part of the loading to be evaporated was therefore justified.

ET Sand Evaluation

The effect of sand size on evaporation performance was evaluated in a limited study. A portion of the Golden ET Sand was passed through a #100 sieve. The finer fraction (<100 mesh) was used in lysimeter #13 and the coarser fraction in lysimeter #17. The size distribution of the two fractions as well as the unaltered Golden ET Sand is shown in Figure 25. The D_{50} value of the unaltered ET sand was 0.13 mm, the finer fraction D_{50} = 0.075 mm and the coarser fraction D_{50} = 0.26 mm.

Three test conditions were used to compare the finer and coarser sands with the unaltered ET sand. These were: (1) constant loading at 1.6 mm/day (0.04 gpd/ft^2), (2) constant water level at 0.23 m (9 in.) below the sand surface, and (3) constant water level at 0.58 m (23 in.) below the sand surface.

During the period of March through August of 1976 the units were loaded at a constant rate of 1.6 mm/day (0.04 gpd/ft^2). The results can be compared to those of the unaltered sand in lysimeter #2. The plot of gravity water level for the three units is shown in Figure 26. The graphs are quite similar except that the rate of evaporation was somewhat less for the coarser sand in June and July, when the gravity water level was low. This reduction in rate was due to the smaller capillary rise potential of the coarser sand.

During the months of October, November and December, 1976, the lysimeters were operated at a constant gravity water level of 0.23 m (9 in.) below the sand surface. The comparable unaltered ET sand lysimeter was #28c. The evaporation rates from the three units were:

finer ET sand = 2.00 mm/day
coarser ET sand = 2.20 mm/day
unaltered ET sand = 2.08 mm/day

These results are quite similar and indicate that for high gravity water levels where all sands had adequate capillary rise potential, the evaporation rate was not affected by sand size.

During the period January through July of 1977 the water level in the units was held at 0.58 m (23 in.) below the sand surface and the evaporation rate was measured and compared with

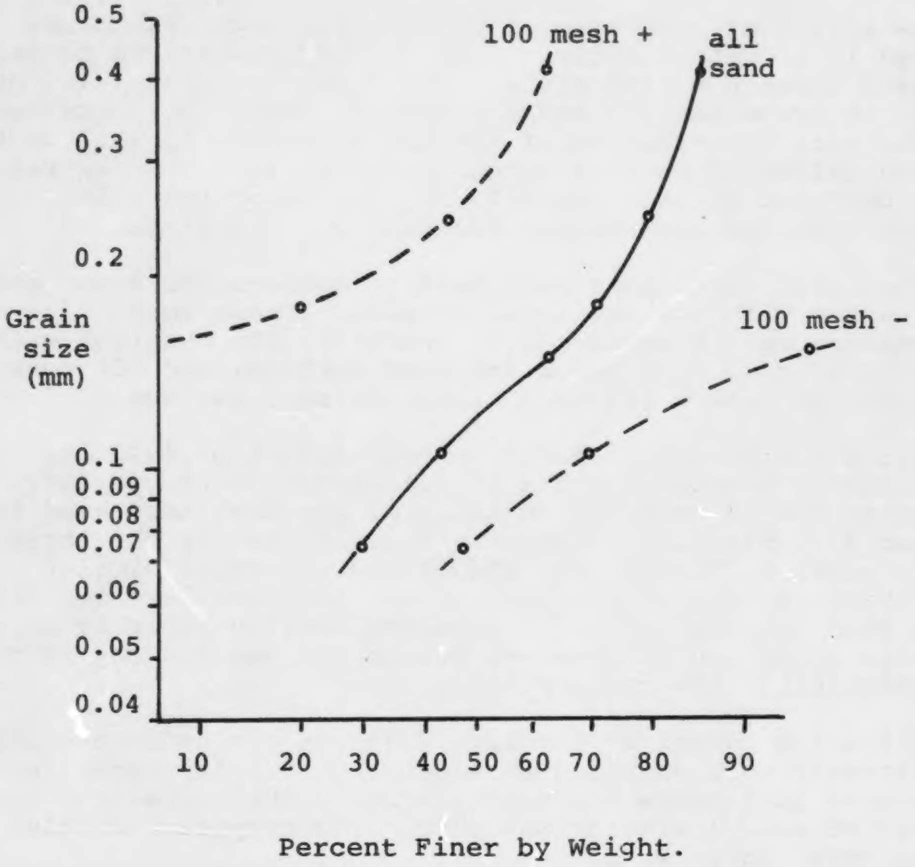
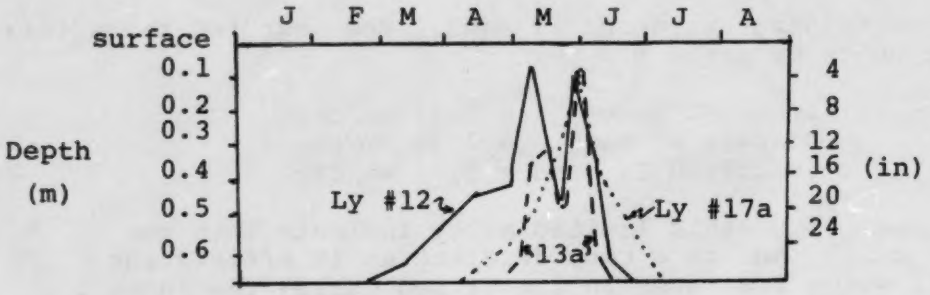


Figure 25. Gradation analysis for Golden sand and for fractions greater and less than 100 mesh.



Gravity Water Level

Key to graph above

Solid line - normal ET sand, Ly #12
Dashed line - fine fraction <200 mesh, Ly #13a
Dotted line - coarse fraction >200 mesh, Ly #17a

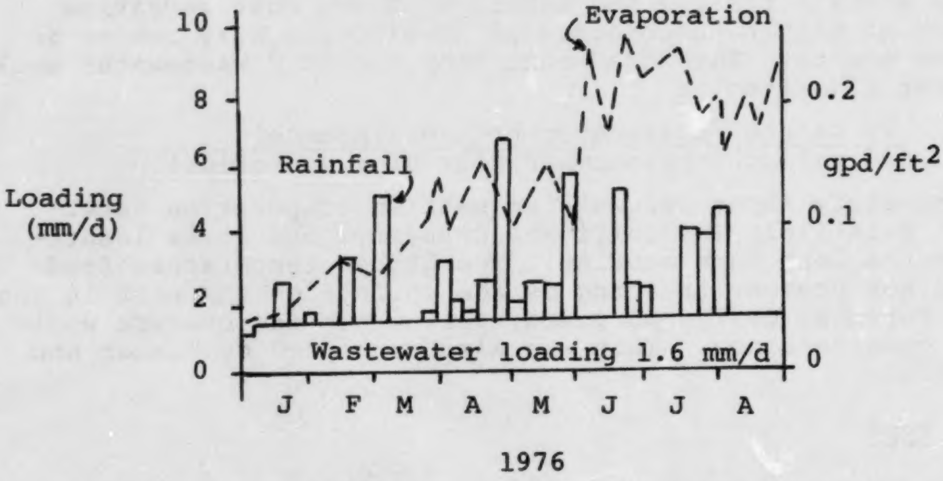


Figure 26. Lysimeter gravity water level as a function of evaporation and water loading for different sized ET sands.

unit #7a containing unaltered ET sand. The measured rates for the three units were:

finer ET sand = 1.32 mm/day
coarser ET sand = 1.20 mm/day
unaltered ET sand = 3.76 mm/day

The results of this limited study indicate that the selection of ET sand is a consideration as it affects the raising of water from deep in the ET bed during the summer. Coarser sands do not provide adequate capillary rise potential and very fine sands or silts may restrict water movement. It has been shown that the summer is not the critical operating period for an ET bed. Therefore, the overall performance, at the nearly constant loading that is characteristic of home wastewaters, would be less affected than these values indicate. However, ET sand selection is important in bed design to allow for maximum loading and ensure optimal performance.

Wastewater Temperature Effect

One of the lysimeters (#5a) in the study was loaded at a rate of 1.6 mm/day (0.04 gpd/ft^2) using wastewater at a temperature of 50°C. The results of the elevated temperature can be compared directly with those of unit #2a, which had identical loading with water at 30°-37°C. The results of the two units are compared in Figure 27. It can be noted that the performance was quite similar for the two units, with the unit receiving wastewater of higher temperature performing slightly better in the winter months. The added heat from the 50°C wastewater would account for a maximum of

$$\frac{\text{20 cal/cc (wastewater heat difference)}}{\text{600 cal/cc (approximate heat of evaporation)}}$$

or approximately three percent increase in evaporation rate. This is a relatively insignificant quantity, but it is identifiable in the long term studies. The higher temperature feed water did not prevent freezing of the surface of the unit in the winter. For most design purposes, wastewater temperature would not be a consideration. This was also concluded by Tanner and Bouma (1975).

Effluent Type

Three types of water were fed to the lysimeters during a brief study in September 1975. The three feed waters were primary effluent and secondary effluent (both from a local sewage treatment plant) and tap water. Six lysimeters were studied in the constant gravity water mode; three with the water level maintained at 0.23 m (9 in.) below ground surface and three with the gravity water level 0.58 m (23 in.) below the sand surface. After a period of operation to achieve equilibration,

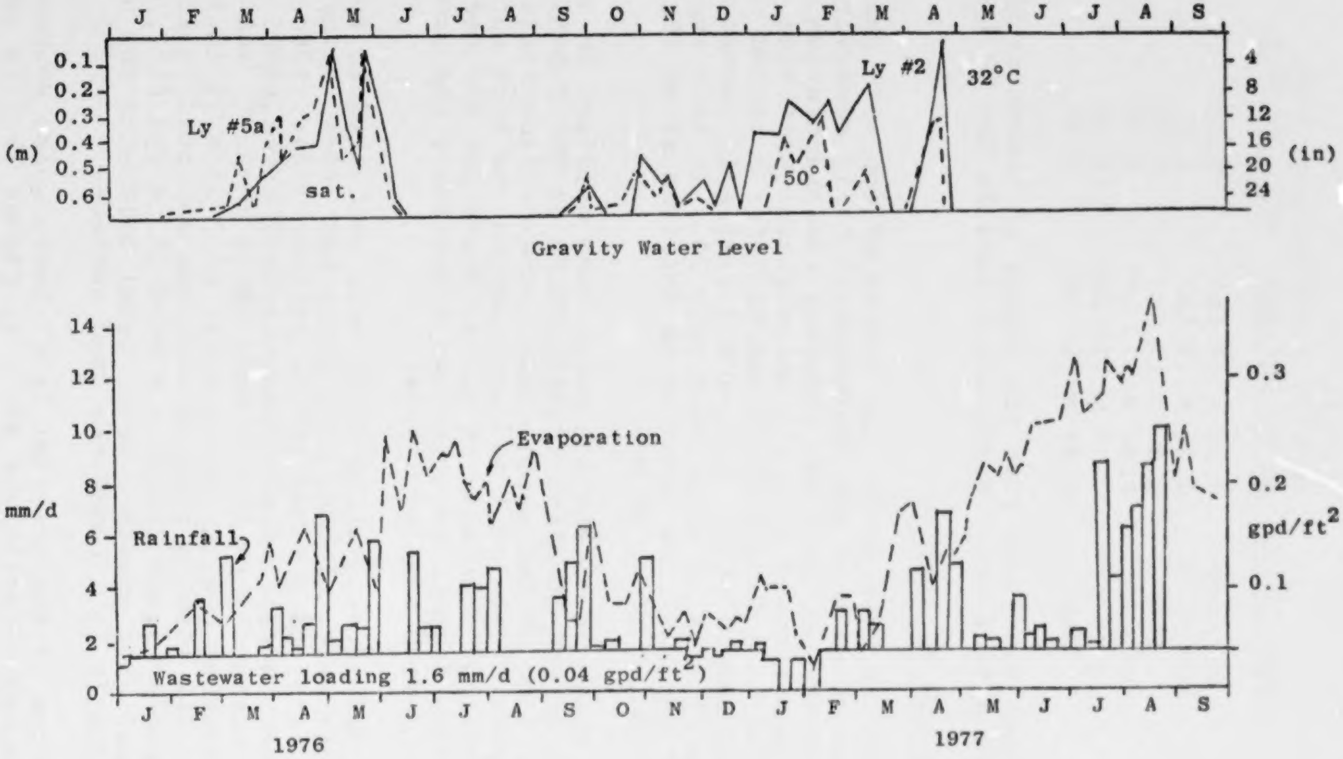


Figure 27. Effect of elevated wastewater temperatures on lysimeter gravity water level.

the evaporation rate was measured for a period of two weeks. The results were as follows:

Lysimeter Number	Feed Water	Depth of Gravity Water Below Surface	Evaporation Rate, mm/day
8f	Primary	0.23 m (9 in)	5.60
4f	Secondary	0.23 m (9 in)	5.46
5f	Tap	0.23 m (9 in)	5.87
25f	Primary	0.58 m (23 in)	4.38
21f	Secondary	0.58 m (23 in)	4.24
28f	Tap	0.58 m (23 in)	4.38

It has been concluded that the degree of treatment of wastewaters did not affect their evaporation rate in the ET lysimeters.

Surface Cover and Vegetation

Initially, in this study, two inches of top soil was placed on the surface of each of the lysimeters. Early observations indicated that the top soil was reducing the evaporation rate. The top soil was removed from all units except unit #10a. The unit was loaded at 1.6 mm/d (0.04 gpd/ft^2) for a period of one year. A comparison of this unit with a similarly loaded unit without top soil (#2) is shown in Figure 28. In this study, a thin layer of top soil was found to be detrimental to the optimum functioning of an ET bed.

Several types of vegetation cover were utilized in order to assess the effect of plant transpiration on the functioning of an ET bed. Two of the shrubs used, pussy willow (#18a) and salt cedar (#27c) (tamarack) did not survive the high water level and freezing conditions of winter operation and resulting evaporation data from these units was essentially the same as that from units with bare soil cover.

Three types of vegetation cover were evaluated in long term studies. These were Kentucky blue grass sod (#11a, #16c), alfalfa (#1), and the juniper shrub, pfitzer (#24c, #26c). The sod and pfitzers were studied using two lysimeters each, one loaded at a constant rate of 1.6 mm/d (0.04 gpd/ft^2) and the other at a constant gravity water level of 0.23 m (9 in.) below the surface. The alfalfa planted unit was operated initially as a constant loading lysimeter at 1.6 mm/d (0.04 gpd/ft^2), and in the second year as a constant water level unit with the water level at 0.23 m (9 in.) below the sand surface.

The results of the constant level tests where evaporation rate was measured directly are shown in Figure 29. It can be noted that alfalfa produces a very high evaporation rate in the summer but that, in the critical winter period, the evaporation rate was considerably below that of bare soil due to the shading

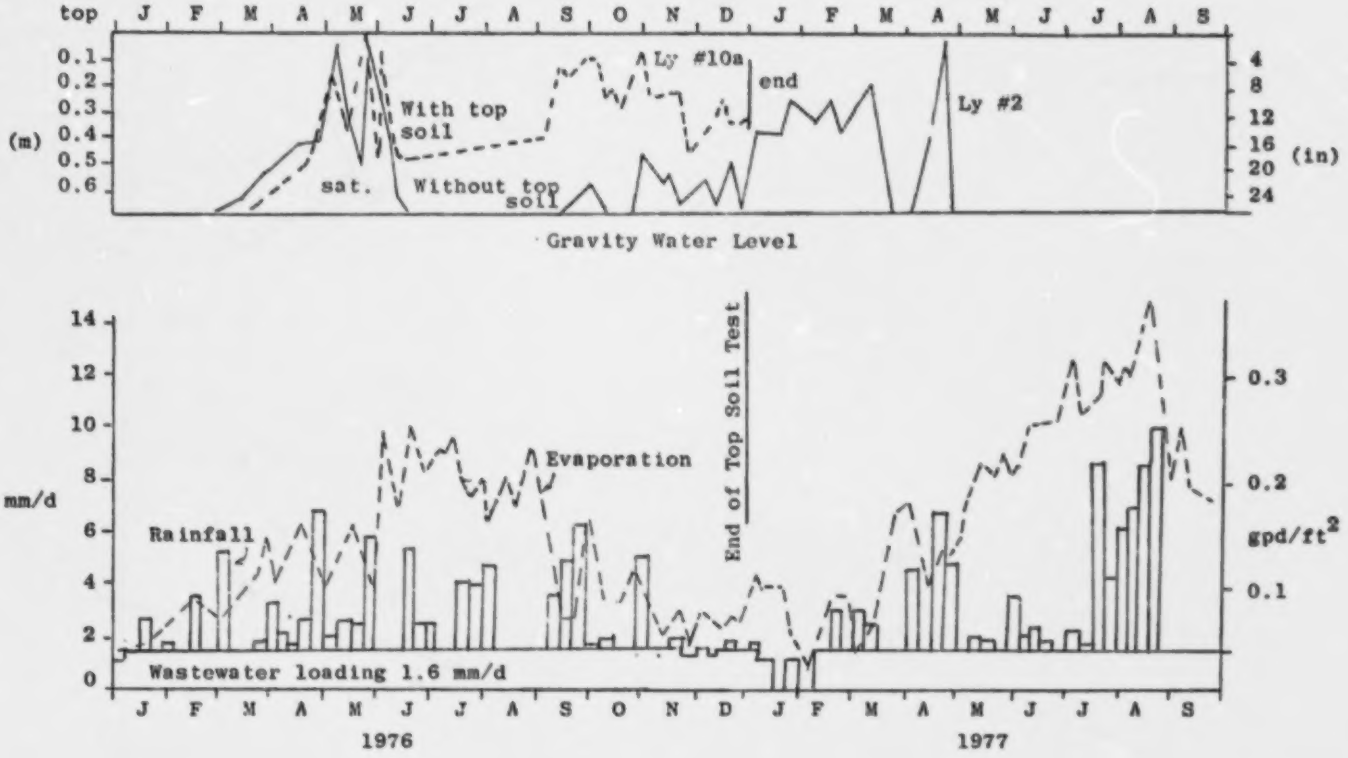


Figure 28. Effect of topsoil cover on lysimeter gravity water level.

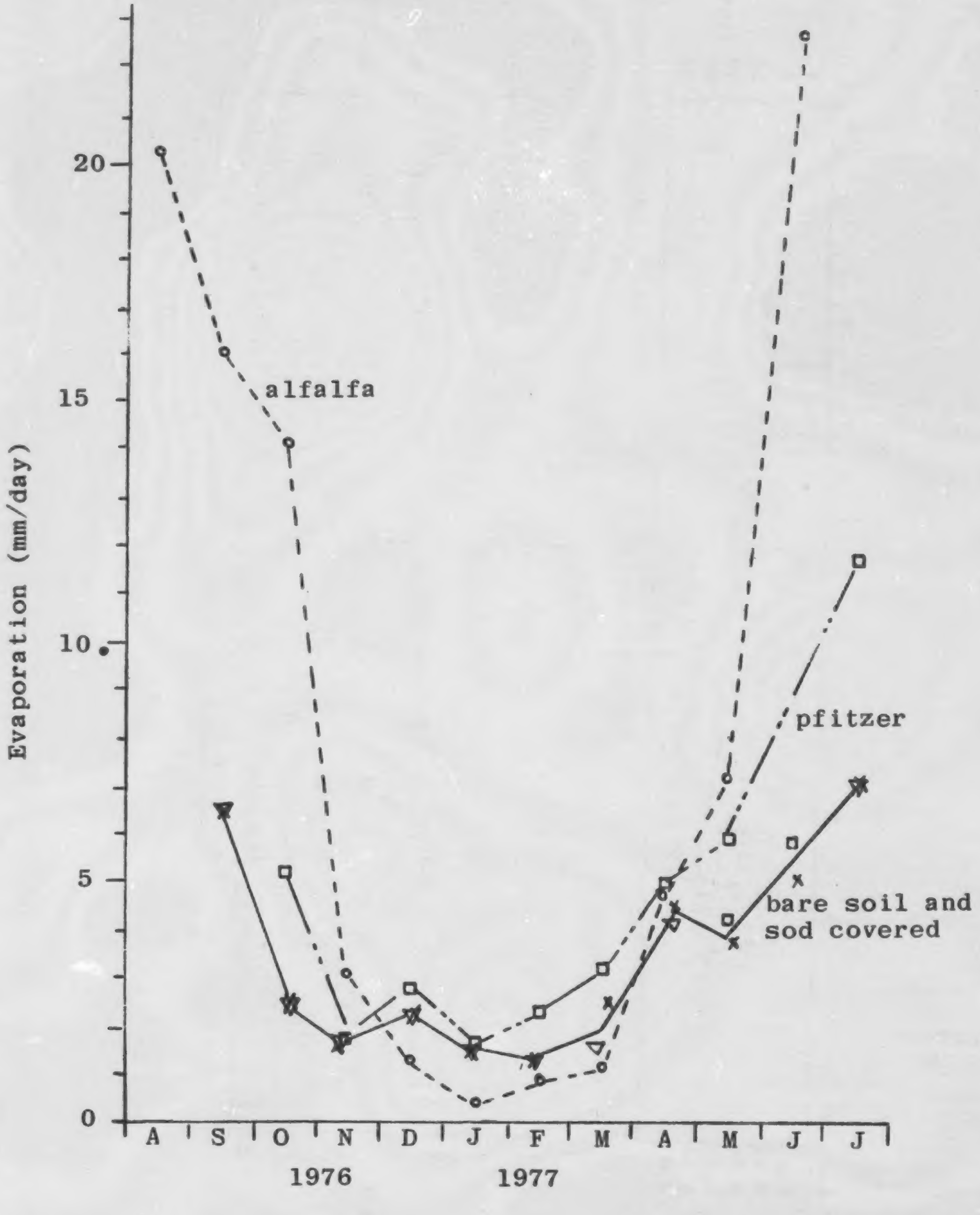


Figure 29. Monthly evaporation rate for different vegetation cover.

and snow holding characteristics of the alfalfa. Sod grass cover produced nearly identical evaporation rates as the bare soil except that it was slightly lower in the important months of March and April. The pfitzer bush produced greater evaporation rates than bare soil throughout the year.

The effects of the evaporation rates on the year round functioning of the lysimeters is shown in Figure 30. These results indicate that the use of pfitzers can be beneficial to the operation of the beds and that grass cover will slightly reduce evaporation rates in the winter and spring.

Another observation that was made during the constant loading studies was that the very dry conditions of the lysimeters in mid-summer were a problem for maintaining vegetation. The alfalfa dried out to the point that it was completely brown in mid-summer, although it did become green again with new growth in the fall when the moisture content of the unit increased.

The sod grass unit, operated at constant loading, was severely affected by the low moisture conditions of summer. The grass gradually died out and gave way to weeds. Although some of the grass remained, it was apparent that maintaining grass on an ET unit would be very difficult with the normal pattern of household wastewater loading and prevailing evaporation conditions of the study area.

The pfitzers did not seem to be adversely affected by the dry conditions of summer or the high water level and freezing conditions of winter. This evergreen showed a high tolerance for soil moisture variations and produced improved evapotranspiration conditions throughout the year.

Near the end of the study, during August and September of 1977, two species of deciduous populus trees, cottonwood and Lombardy poplar, were planted in five of the lysimeters. Three of the units were operated at a constant gravity water level of 0.23 m (9 in.) below the surface in order to measure evaporation rates. One tree of each type was evaluated at a constant loading of 1.6 mm/d (0.04 gpd/ft^2) of wastewater to provide information on the survival of this type of tree under summer conditions. The lysimeters used were as follows:

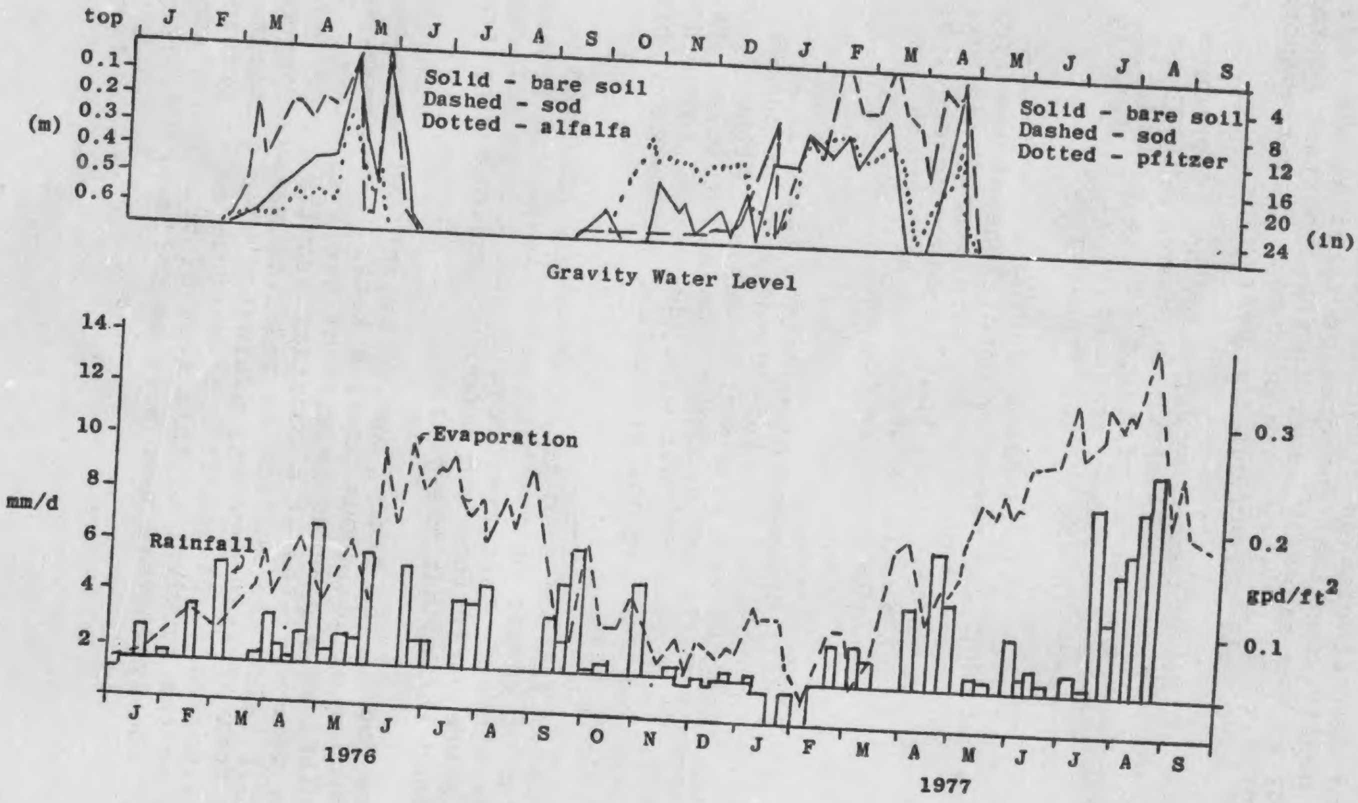


Figure 30. Effect of vegetation cover on lysimeter gravity water level.

Lysimeter Number	Tree Type	Leaf Area (one side)	Loading	Gravity Water Level	Evaporation Rate
12e	cottonwood (2m)	1.0 m^2 (400 leaves)	variable	0.23 m (9 in.)	12.8 mm/d
18e	poplar (1.5m)	0.007 m^2 (200 leaves)	variable	0.23 m (9 in.)	7.25 mm/d
23e	poplar (1.5m)	0.12 m^2 (350 leaves)	variable	0.23 m (9 in.)	11.07 mm/d
7e	cottonwood (2m)	0.75 m^2 (300 leaves)	1.6 mm/d (0.04 gpd/ft^2)	variable	-
22e	poplar (1m)	0.08 m^2 (250 leaves)	1.6 mm/d (0.04 gpd/ft^2)	variable	-

The cottonwood trees had leaves that were triangular in shape with an average base and height measurement of 7 cm (2-3/4 in.). The leaves of the poplar trees were smaller, having base and height measurements of 1.3 cm (1/2 in.).

The bare soil evaporation rate for this testing period was 5.8 mm/day. The use of small deciduous trees increased the evapotranspiration rate by as much as one hundred percent in August and September compared with bare soil. However, the two trees that received a constant wastewater loading of 1.6 mm/day (4.0 mm/day including rainfall) showed severe signs of wilting, especially the larger cottonwood tree (#7e).

Deciduous trees have a large water requirement in the summer growing season and this is the period when an ET bed is subject to its driest conditions. In addition, this type of tree provides negligible transpiration in the dormant winter months which is the critical time when extra evapotranspiration potential is needed for an ET bed. The type of ET beds evaluated in this study do not provide enough storage so that winter flows can be held for evaporation during the subsequent summer period. Since deciduous trees do not aid in winter disposal and because their water requirements are high in the summer, they are not suited to be used as an evapotranspiration adjunct for the type of ET bed studied. A completely different type of bed could be considered, designed with enough depth to provide for storage of wastewater generated throughout the dormant season and disposal primarily by transpiration in the summer. This type of system was not a part of this study.

For the type of ET bed evaluated in this study, small evergreens seem to provide the practical choice of vegetation in conjunction with bare soil or with grass or weed surface coverings. The evergreens provide some transpiration in the winter which aids disposal to a small extent and they seem to tolerate the dry soil conditions present in the summer period.

The design of ET systems for summer homes could utilize highly transpiring plants such as alfalfa, resulting in higher loading rates.

Salt Build-Up

Salt build-up in a non-discharging ET bed will have a long term effect on surface vegetation. The total dissolved salts in home wastewater have been found to be in the range of 400 to 500 mg/L (Bennett, Linstedt, 1975). For a loading rate of 1.6 mm/day (590 liters/yr·m^2) (0.04 gpd/ft^2) the salt increase would be about 270 gm/yr.m^2 (25 gm/yr/ft^2). A two foot deep bed with a porosity of 0.35 would contain 20,000 grams of water at saturation and 100,000 grams of ET soil. The average salt build-up would be approximately 1250 mg/ℓ per year in the water or 0.25 mg/yr/gm of soil. The salts tend to concentrate at the evaporative surface. A measurement was made of the elutriate of the surface sand of a home ET bed system that had been in operation for five years. The total salt level was found to be 11.5 mg/gm of soil with 0.91 mg of chloride/gm of soil. At soil water saturation conditions, this would represent a total salt concentration of 50,000 mg/ℓ and a chloride concentration of 4500 mg/ℓ. The build-up of salts over a period of years in a non-discharging ET bed would be an important factor in the design consideration of utilizing plant transpiration to increase the ET rate.

FIELD OBSERVATIONS OF ET BEDS

Five ET units installed and in use at individual homes were observed every few weeks. The water use rate of the homes was not measured and the loading rates were estimated based on the size of the ET bed and the number of occupants of the home. Using a value of 170 liters per person per day (45 gal/per/day) for the estimation, the wastewater loading rates varied from 0.8 mm/day to 4.0 mm/day (0.02 to 0.10 gpd/ft^2). The units with loadings of 0.8 to 2.0 mm/day (0.02 to 0.05 gpd/ft^2) appeared to perform satisfactorily during the study period. Each of the units had a center stand pipe for observing the water level in the bed. None of the units within this loading range became completely filled during the period of observation.

Two ET beds had estimated loading rates of 2.4 mm/day and 4 mm/day (0.06 and 0.10 gpd/ft^2). The bed with the highest loading experienced frequent saturation with subsequent ponding and runoff. The other ET bed filled at times and the owners stated that during those periods they had reduced bed loadings by washing their clothes at a laundromat. Another unit in the area, which was not monitored during this study, had an estimated loading of 3.2 mm/day (0.08 gpd/ft^2). Due to frequent saturation of the bed, a second bed of equal size was installed to reduce the estimated loading to 1.6 mm/d (0.04 gpd/ft^2). The field observations provided information that the maximum satisfactory loading rate was approximately 1.6 mm/d (0.04 gpd/ft^2), the same as that determined in the lysimeter study.

RESULTS OF MECHANICAL EVAPORATION UNIT STUDIES

Studies of the two types of mechanical units were made and the results presented in a sequence for each unit involving the basic operational parameters followed by tests relating to optimization of machine design variables.

Rotating Disk Evaporator (RDE)

It has been shown that the rate of evaporation from a wetted surface can be described using a mass transfer approach where the major parameters are the humidity deficit of the air in contact with the wetted disks and direct solar radiation. The general equation can be written as

$$E = k_1(\Delta H) + k_2 R_S$$

Since contribution of direct solar radiation is relatively small, a major portion of the study was involved in defining the parameters affecting the mass transport coefficient, k_1. In the study of a device of this type, it is important to isolate each parameter while maintaining the others at constant values. Many of the results were obtained during operation of the unit in the laboratory under conditions of constant air temperature and humidity deficit. This approach was used to study the effects of wind speed and direction, disk size and area, rotational speed and disk spacing. Studies were made under field conditions with the unit operated on the roof of the Engineering Center to establish the effect of a wide variation in temperature and humidity deficit as well as the contribution from direct solar radiation. The data obtained under field conditions show more variation or scatter than those from the laboratory studies. In order to obtain an accurate measure of evaporation rate, the unit was operated for a minimum of two hours. During this period, temperature and humidity variations occurred in the ambient air. Average values of temperature and humidity were obtained from the recorder charts and used in the data analysis. The somewhat lower precision for field data was due to this variation in ambient conditions.

Liquid Mixture Temperature--

As evaporation proceeds in an adiabatic process, an equilibrium will be established in the liquid where the gain in sensible heat from the air will equal the loss in latent heat due to evaporation. At equilibrium the temperature of the water will equal the adiabatic saturation temperature of the air.

Figure 31 shows the bulk mixture temperature as a function of the adiabatic saturation temperature of the ambient air under laboratory and field conditions for the rotating disk unit. This figure shows that the bulk mixture temperature correlated reasonably well with the adiabatic saturation temperature of the ambient air. The value of the adiabatic saturation temperature, T_s, was computed using the psychrometric chart and measured values of the air temperature and relative humidity at the time the mixture temperature was recorded. The air temperature in all cases was at least 5^oC above the mixture temperature. From these results, it can be concluded that the liquid temperature is approximately the same as the adiabatic saturation temperature of the ambient air and that the measured humidity deficit will represent the adiabatic humidity deficit for evaporation from the disk surface.

Adiabatic Humidity Deficit--

The equation for evaporation rate is based on a linear relationship between adiabatic humidity deficit and evaporation rate in the absence of direct solar radiation. In order to study this relationship under a wide range of temperature and humidity conditions while holding other major parameters constant, studies were made in the laboratory and outdoors using the wind tunnel. This produced a nearly constant wind speed and excluded sunlight.

The results of these studies are shown in Figure 32. The wind direction was at 90^o angles to the shaft (parallel with the disks) and the disk rotational speed was 0.5 rpm. It can be concluded from these data that a linear relationship exists between evaporation rate and humidity deficit of the ambient air. Studies at lower wind speeds were attempted outdoors but the ambient wind changes made it impossible to maintain a constant air velocity across the disks for the period of measurement.

Wetted Disk Area--

For mass transport operations, the usual assumption is that the rate of the process is directly proportional to the interfacial area involved. The exposed surface area of the multiple disk evaporator can be varied by changing the submergence (depth of water in the reservoir) or by using a different diameter disk.

The segmented reservoir was used in laboratory studies to study four different submergence levels simultaneously under the same ambient conditions. Four different tests were conducted using the wind tunnel at various wind speeds. The results are shown in Figure 33. It can be noted that the evaporation rate per unit of wetted disk area was essentially constant at all submergences. The maximum wetted area occurs at a submergence of approximately seventy-one percent of the radius measured from the outer edge and this value should be used in prototype units.

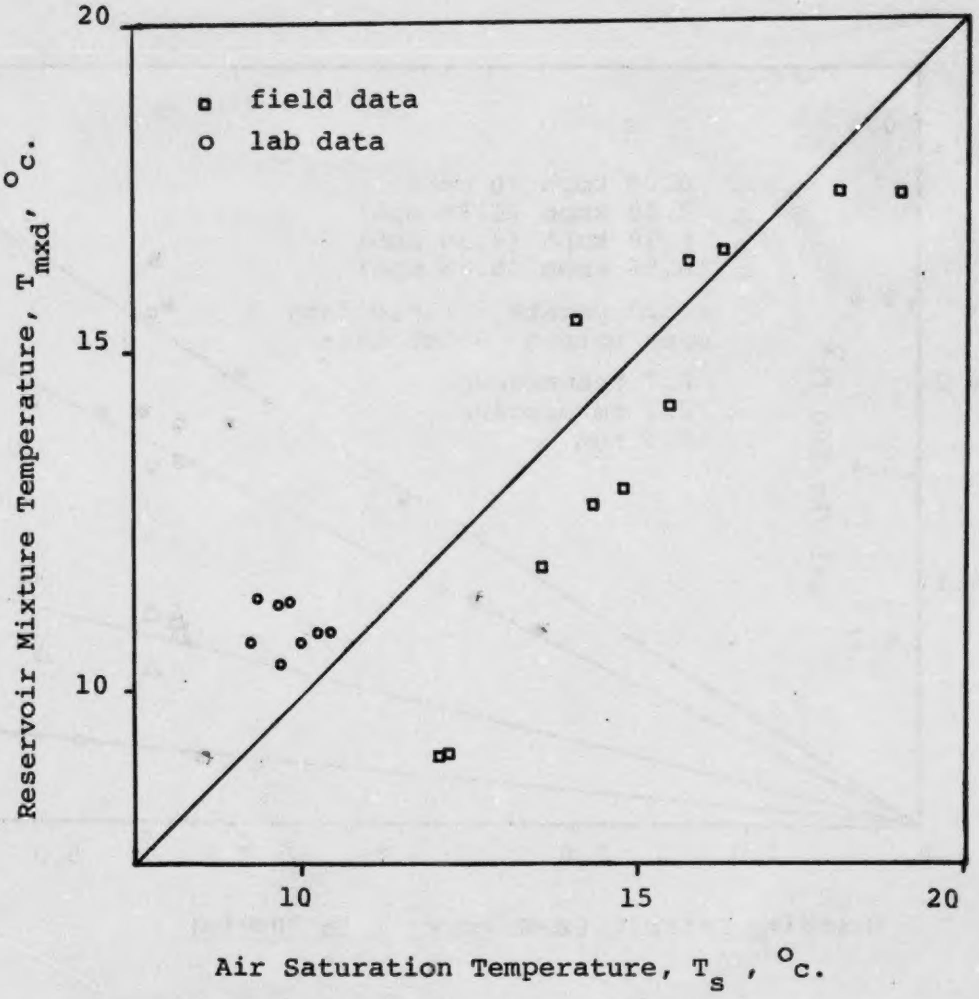


Figure 31. Rotating disk unit bulk mixture temperature, T_{mxd}, as a function of adiabatic saturation temperature of the ambient air, T_s.

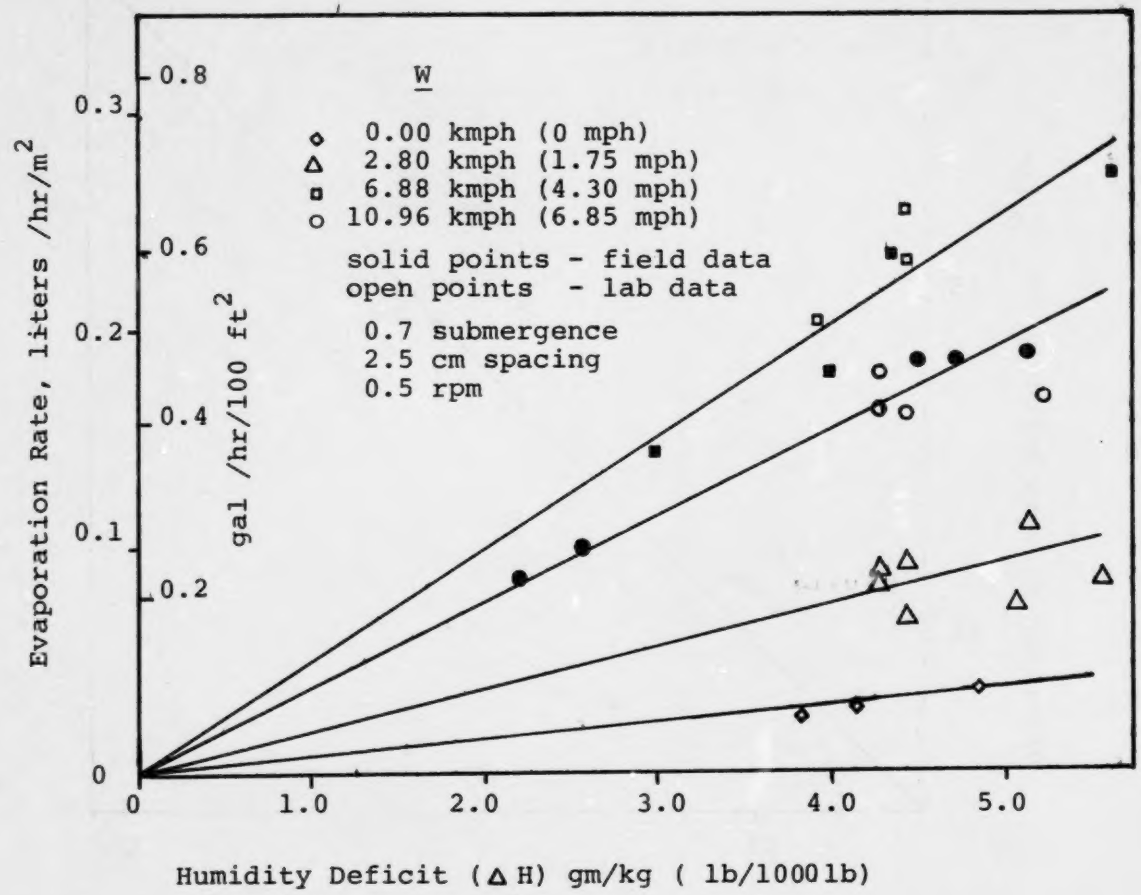


Figure 32. Evaporation as a function of adiabatic humidity deficit for aluminum disk unit in wind tunnel.

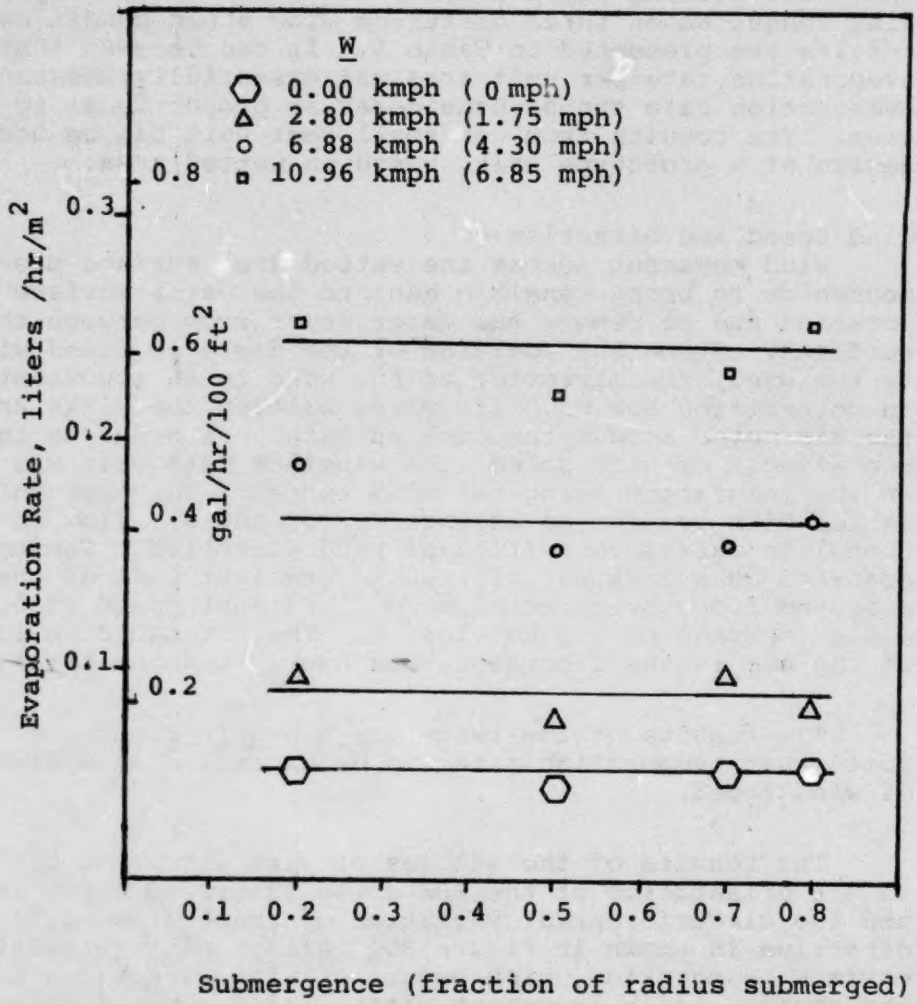


Figure 33. Evaporation as a function of disk submergence for the multi-diameter plywood disk unit in the laboratory.

A larger, three segment reservoir was used to evaluate the effect of disk size. Plywood disks of 0.52 m, 0.91 m, and 1.22 m (20.4 in., 36 in. and 48 in.) were evaluated at a submergence of 0.7, spacing of 2.5 cm (1 in.) and rotational speed of 0.5 rpm. The testing was accomplished in the laboratory using the wind tunnel under three different wind speed conditions. The results are presented in Table 8. It can be seen that the evaporation rate per unit area was essentially constant and that evaporation rate can be considered as proportional to wetted area. The results from the small test unit can be used for the design of a prototype unit, based on wetted area.

Wind Speed and Direction--

Wind movement across the wetted disk surface provides a mechanism to bring sensible heat to the water surface for evaporation and to remove the water vapor from between the disk surfaces. Since the position of the disks is fixed with respect to the wind, the direction of the wind is an important variable in determining how much air moves between the disks and how fast the air moves across the disk surface. In order to investigate the effects of wind speed, the aluminum disk unit was operated in the laboratory using the wind tunnel. The test unit was varied with respect to orientation of the air flow in the wind tunnel to assess the effect of wind direction. The unit was operated at a constant disk submergence of 0.71 of the radius as measured from the outer edge, a rotational speed of 0.5 rpm, and a disk spacing of 2.5 cm (1 in.). The adiabatic humidity deficit of the air in the laboratory was nearly constant at 4.45 gm/kg

The results of the tests are shown in Figure 34. It can be noted that evaporation rate can be expressed as a linear function of wind speed.

The results of the studies of wind direction with respect to the orientation of the RDE drive shaft are shown in Figure 34 and the circumferential variation of evaporation with wind direction is shown in Figure 35. All points are relative to the maximum evaporation which occurs at wind directions of 90° with the shaft. It is important that a field installation should be oriented with the disks parallel to the major prevailing wind direction. Most of the laboratory studies were made with wind movement perpendicular ($\theta = 90^{\circ}$) to the shaft.

Study of Machine Variables--

The major machine variables that were varied and evaluated in this study were: disk submergence, rotational speed of the

TABLE 8. EVAPORATION FROM 3 DIFFERENT DIAMETER PLYWOOD DISK UNITS UNDER CONTROLLED IDENTICAL CONDITIONS (English Units)

Date	Δt hr	E_1 $\frac{gal/hr}{100\ ft^2}$	E_2 $\frac{gal/hr}{100\ ft^2}$	E_3 $\frac{gal/hr}{100\ ft^2}$	W mph	ΔH $\frac{lb}{1000\ lb}$	Disk Spacing (X) in.	R_d rpm
2/22/77	21.50	0.38	0.36	0.38	4.78	5.21	1.0	0.5
2/22	4.00	0.50	0.52	0.56	7.61	4.93	1.0	0.5
2/23	19.00	0.18	0.16	0.19	1.95	5.00	1.0	0.5
2/23	3.75	0.54	0.53	0.54	7.61	5.00	1.0	0.5
2/24	19.00	0.17	0.15	0.18	1.95	5.00	1.0	0.5
2/24	7.00	0.32	0.33	0.35	4.78	5.00	1.0	0.5

Diameter - D_1 = 20.4 in.
D_2 = 36.0 in.
D_3 = 48.0 in.
θ_w = 90°

TABLE 8. EVAPORATION FROM 3 DIFFERENT DIAMETER PLYWOOD DISK UNITS UNDER CONTROLLED IDENTICAL CONDITIONS (S.I. UNITS)

Date	Δt Hr	E_1(0.52 m) $\ell/hr\cdot m^2$	E_2(0.91 m) $\ell/hr\cdot m^2$	E_3(1.22 m) $\ell/hr\cdot m^2$	W kmph	ΔH $\frac{gm}{1000\ kg}$	Disk Spacing (X) cm	R_d rpm
2/22/77	21.50	0.15	0.15	0.16	6.88	5.21	2.5	0.5
2/22	4.00	0.21	0.21	0.23	10.96	4.93	2.5	0.5
2/23	19.00	0.073	0.065	0.08	2.80	5.00	2.5	0.5
2/23	3.75	0.22	0.23	0.22	10.96	5.00	2.5	0.5
2/24	19.00	0.070	0.062	0.073	2.80	5.00	2.5	0.5
2/24	7.00	0.131	0.135	0.143	6.88	5.00	2.5	0.5

Diameter = D_1 = 0.52 m

D_2 = 0.91 m

D_3 = 1.22 m

$\theta_w = 90^\circ$

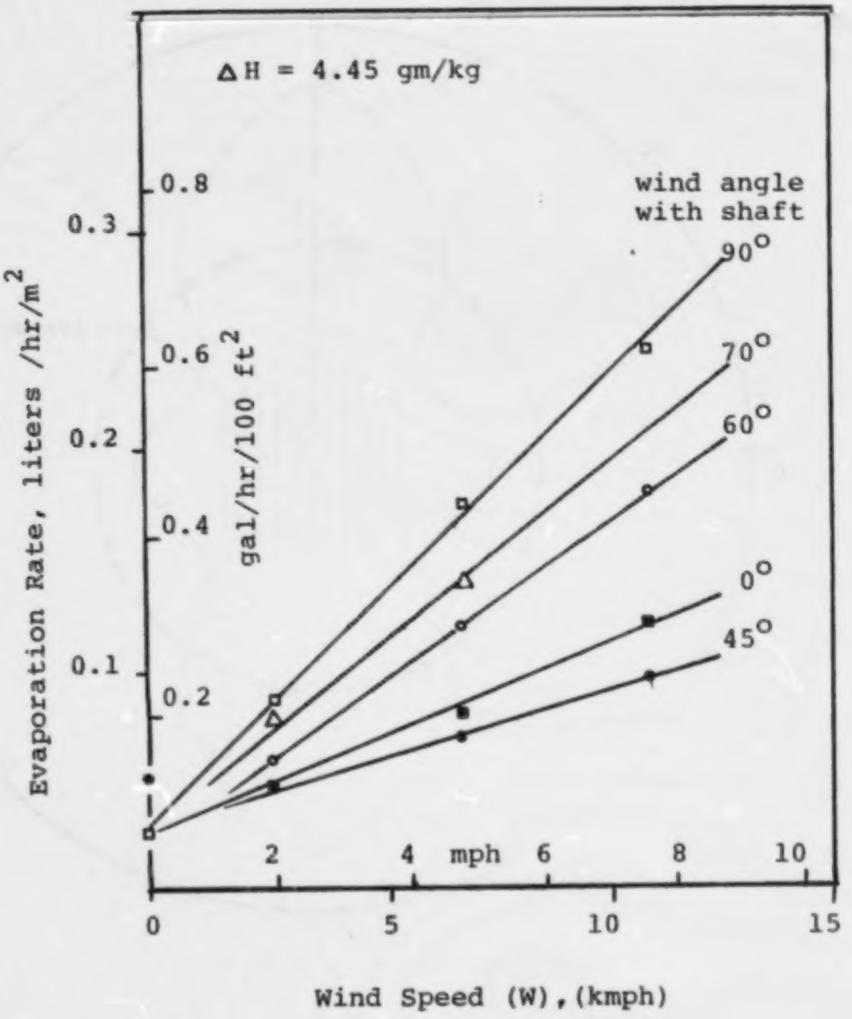


Figure 34. Evaporation as a function of wind speed for the aluminum disk unit in the laboratory wind tunnel at various wind directions.

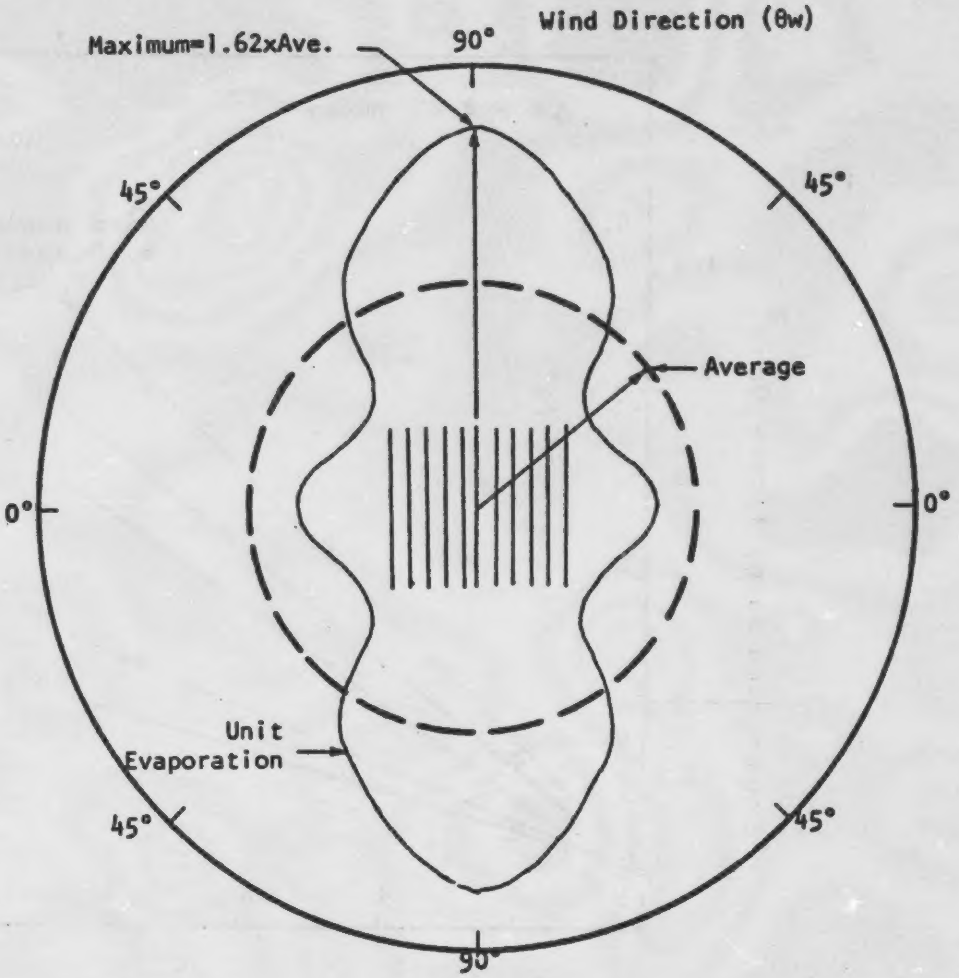

Wind Direction (θw)
Maximum=1.62xAve.
90°
45°
45°
Average
0°
0°
Unit Evaporation
45°
45°
90°

Figure 35. Circumferential variation in evaporation with wind direction relative to 90°.

disks, spacing between the disks and type of material and color of the disks. The results relating to submergence were presented in the section on interfacial area. The rate of evaporation was found to be proportional to exposed wetted surface area and the geometry of the unit is such that a submergence of seven-tenths of the radius results in the maximum evaporation rate.

Rotational speed--The rotational speed of the multi-diameter plywood disk unit was varied from 0.5 to 2.0 revolutions per minute at different wind speeds to study the effect of rotational speed on evaporation. Figure 36 shows evaporation as a function of wind speed for rotational speeds of 0.5, 1.0, and 2.0 rpm. The submergence was constant at 0.7 and the disk spacing was constant at 5 cm (2 in.). The points shown in Figure 36 represent the mean of the data from the three different diameter units, and also represent the mean of at least three separate determinations of evaporation at any one wind speed. The evaporation rate was found to be independent of rotational speed at rotational speeds above 0.5 rpm. The minimum rotational speed must be great enough to keep the disk surface wet during its exposure to the ambient air, but increased rotational speed beyond that point does not increase evaporation. Greater rotational speeds will meet the wetting requirement, but may tend to cause more power consumption and more wear on mechanical parts. The optimum rotational speed was found to be the slowest speed necessary to keep the disks wet. This was found to be approximately 0.5 to 1.0 rpm.

Disk spacing--Wind speed and wind direction have been shown to be important parameters in the evaporation of wastewater using the rotating disk unit. Closely associated with wind speed and direction is horizontal disk spacing on the drive shaft. As disk spacing increases, the wind will be able to move between the disks more easily. An increase in wind movement will in turn increase the transfer of sensible heat from the air to the water and the transfer of water vapor from the water surface to the overlying air. Large disk spacings will enhance heat and mass transfer per unit of wetted disk area up to some point, yet large disk spacings will also increase the unit size and capital costs. The multi-diameter plywood disk unit was operated at a constant rotational speed of 0.5 rpm and a constant disk submergence of 0.7 in the wind tunnel in order to investigate the effect of disk spacing on evaporation. Disk spacings of 1.25, 2.5 and 5 cm (0.5, 1.0, and 2.0 in.) were used during the test. Figure 37 shows the results of the study on disk spacing.

The points shown in the figure represent the mean value obtained from the three different diameter units and the mean from at least two separate determinations of evaporation at a single wind speed. The wind direction was 90° with respect to the drive shaft in all cases. There was an increase in evaporation with disk spacing at the wind speeds obtained in the wind

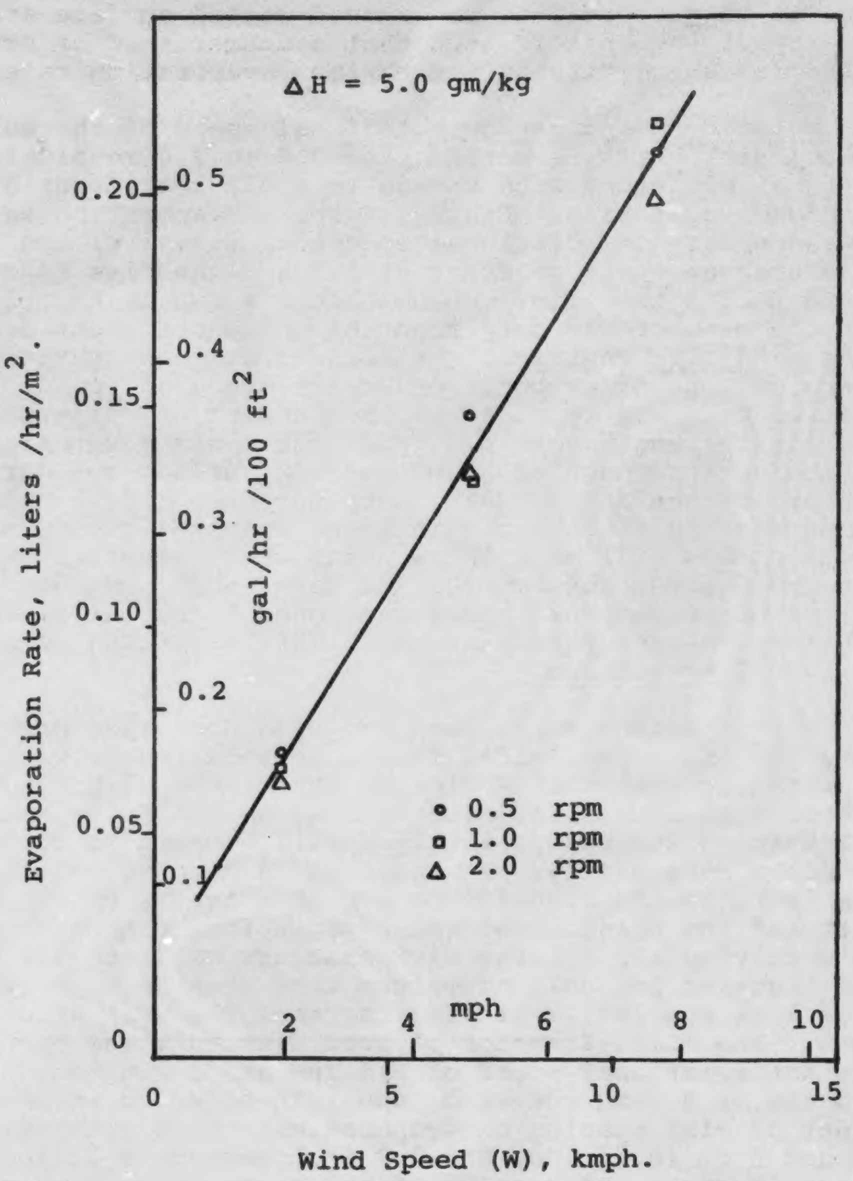


Figure 36. Evaporation as a function of wind speed for various rotational speeds.

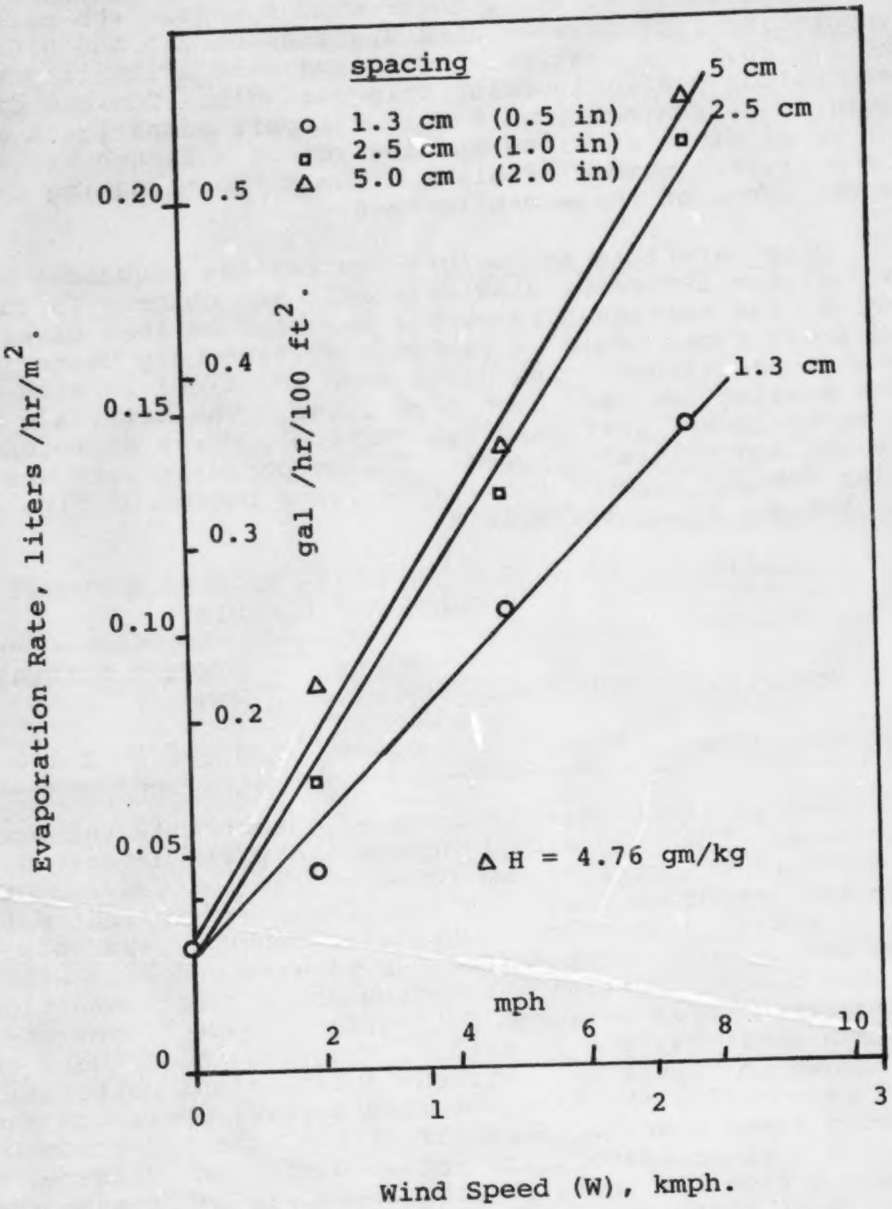


Figure 37. Evaporation as a function of wind speed for various disk spacings.

tunnel. There was a substantial increase in evaporation when the disk spacing was increased from 1.25 to 2.5 cm (0.5 to 1.0 in.), especially at the greater wind speeds. The difference in evaporation rate between disk spacings of 2.5 and 5.0 cm (1.0 and 2.0 in.) was smaller, indicating that a limiting value of evaporation was influencing this variable. Optimum disk spacing could be determined from a cost analysis comparing a larger number of disks at close spacing versus a larger vat and shaft for a smaller number of disks. The optimum spacing is probably in the range of three centimeters.

Disk materials and color--Two testing sequences were used to evaluate different disk materials and color. In the first series, the sectioned reservoir was used so that disks of several different types could be tested simultaneously under identical ambient conditions. The disks were identical in size and the same spacing was used with each group. The materials used were aluminum (gray, well oxidized surface), white styrofoam, black plywood and natural plywood. The evaporation rate was measured under ambient outdoor conditions for a period of five days. The results are shown in Table 9.

TABLE 9. 24 HOUR EVAPORATION RATE AS A FUNCTION OF DISK COLOR AND MATERIAL

Material	Gray Aluminum	White Styrofoam	Black Wood	Natural Wood
Evap ℓ/hr	0.101	0.079	0.097	0.100

Most of the materials produced essentially the same evaporation rate. The only exception was the white styrofoam. In order to gain an insight into the cause of the reduced evaporation with the styrofoam disks, an experiment was initiated to evaluate the effect of disk color. The two-chambered reservoir unit was used and plywood disks painted white were compared with disks painted black. Testing was done under ambient conditions with evaporation rates measured during the middle of the day with maximum sunlight, and at night. The results of these studies are shown in Figure 38. Without sunlight the evaporation rates were essentially the same. During daytime operation the black plywood disks absorbed more direct sunlight radiation and produced a greater evaporation rate. During the daytime, the evaporation from the white plywood disks was about seventy-nine percent of that of the black disks. The data in Table 9 was obtained on 24 hr operation and the solar radiation was less than one-half of the value during daytime testing. If color were the only factor involved, it would be expected that the white disks would evaporate about 90 percent as much as the black on a 24 hr basis. Since the white styrofoam evaporated about 80 percent as much as the black plywood on a 24 hr basis, it can be

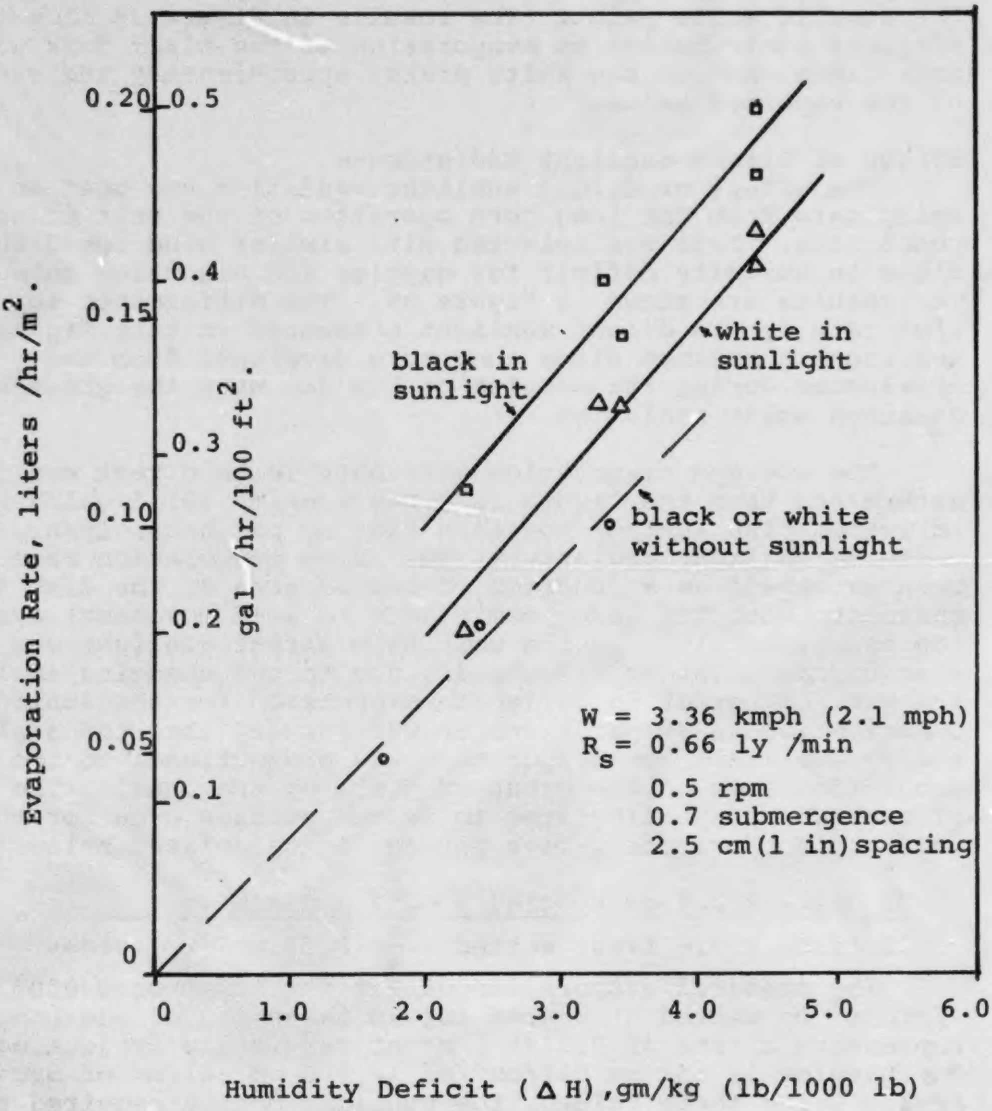


Figure 38. Evaporation as a function of adiabatic humidity deficit for disks of different colors.

concluded that a portion of the reduced evaporation of the styrofoam was due to the white color and a significant portion was due to the nature of the material. Duffie and Beckman (1974) have shown that the absorbance of solar energy was 98 percent for parson's black colored surfaces as compared to 26 percent for acrytic white paint. The results in Figure 38 show that the sunlight contribution to evaporation of the black disk was about four times that of the white disks, approximately the same range as the reported value.

Effect of Direct Sunlight Radiation--
The effect of direct sunlight radiation has been assessed using data from the long term operation of the unit under ambient conditions. Data was selected with similar wind speed and variations in humidity deficit for daytime and nighttime measurements. The results are shown in Figure 39. The differences in evaporation rate due to direct sunlight presented in this figure represent a maximum since they were developed from the data in mid-summer during the portion of the day with the greatest measured solar radiation.

The average evaporation attributable to direct sunlight as determined from the figure is $0.044\ \ell/\text{hr/m}^2$ (0.11 gal/hr/100 ft^2) of wetted disk surface for each Langley per hour, ly/hr, of measured sunlight radiation. The above evaporation rate has been expressed as a function of wetted area of the disk to correlate with the aerodynamic (due to wind movement) evaporation. The energy received by the unit from direct sunlight was somewhat variable throughout the day due to the changing angle of the sun. In order to derive an expression for the sunlight contribution to evaporation, it was assumed that the sunlight energy available for evaporation was proportional to the vertical projection area of the group of disks on the shaft. The ratio of vertical projecting area to wetted surface area for the test unit was approximately five percent as calculated below:

$$\frac{23 \text{ disks} \times 2.5 \text{ cm spacing} \times 0.52 \text{ m diameter}}{23 \text{ disks} \times 0.6 \text{ frac. wetted} \times \frac{\pi}{4}(0.52 \text{ m})^2 \times 2 \text{ sides}} = 0.051$$

The measured evaporation of $0.044\ \ell/\text{hr/m}^2$ or $0.00073\ \ell/\text{min/m}^2$ of wetted disk area for an intensity of one Langley represents a rate of $0.0146\ \ell/\text{m}^2$ of vertically projecting area. One Langley is one gm cal/cm^2 or 10,000 gm cal/m^2 of projected area. Using these values, the sunlight energy required to evaporate one gm of water is 10,000 gm cal/14.6 gm = 685 cal. The theoretical heat of vaporization of water at the test conditions is 588 cal/gm. The apparent efficiency of solar radiation capture for the unit is approximately eighty-six percent. although one would assume that the wetted, oxidized aluminum disks would have a reflectance greater than 14 percent, the close spacing of the disks causes much of the reflected energy to be

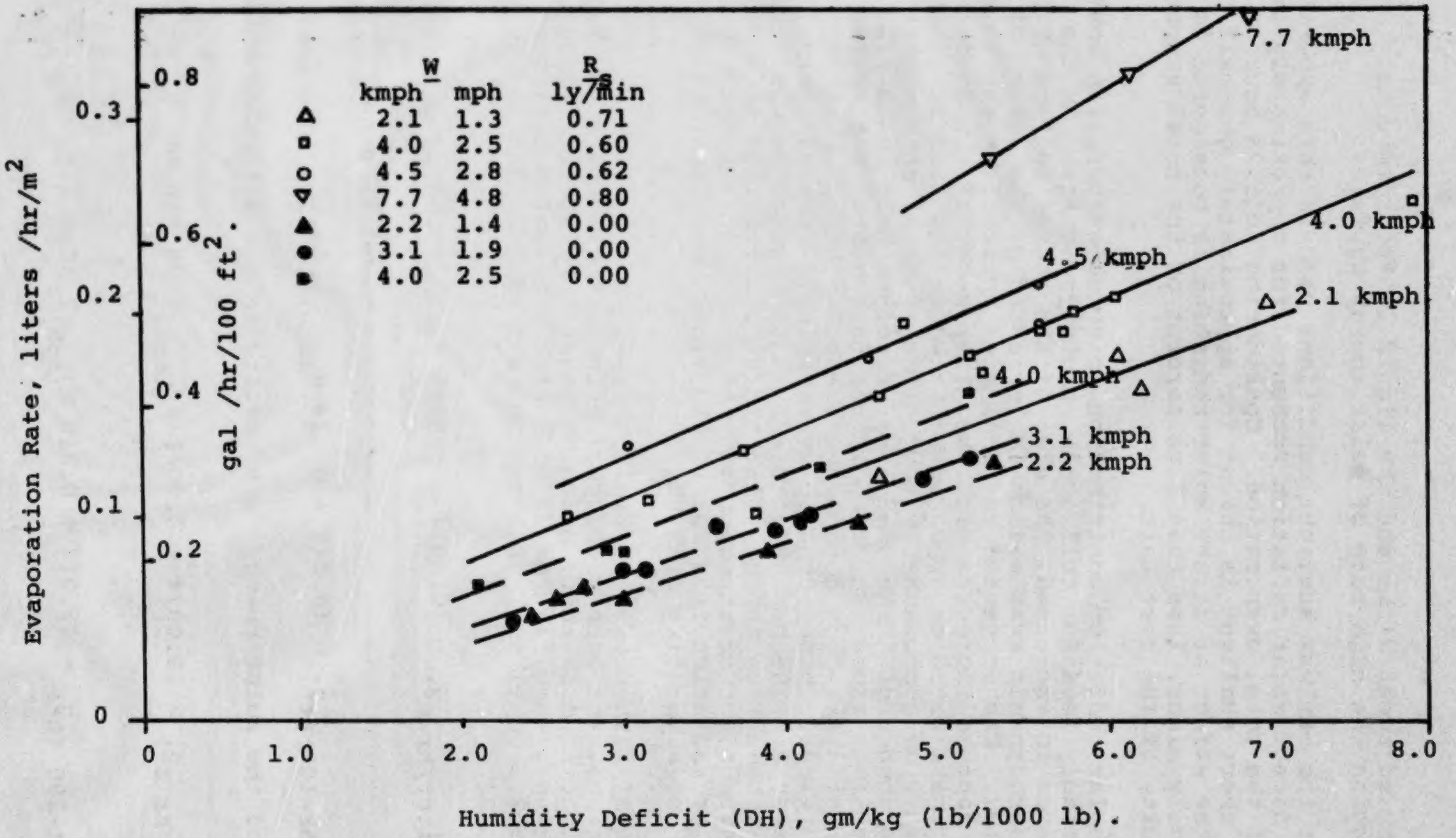


Figure 39. Evaporation as a function of adiabatic humidity deficit for the aluminum disk unit operating under field ambient air conditions.

captured by adjacent disks and the liquid in the reservoir, thus producing the high rate of solar energy capture.

Under the maximum sunlight conditions used in this experiment, the direct solar radiation accounted for approximately ten percent of the total evaporation. Considering full 24 hour operation where sunlight is absent for approximately one-half of the day, the effect of direct solar radiation is considered to be relatively minor, less than five percent of the total evaporation capacity of the test unit.

The solar radiation contribution to total evaporation would be considerably less for full scale, prototype units. As the disk diameter is increased, the area of the wetted surface which controls aerodynamic evaporation is increased by the square of the diameter. The projected vertical area controlling the solar radiation capture increases with the first power of the diameter. Prototype units would be approximately two meters (6.5 ft) in disk diameter or approximately four times as great as the test unit. The number of disks used in a prototype unit would also be three or four times that used in the test unit. Increasing the number of disks does not change the solar energy contribution with respect to aerodynamic evaporation. Increasing the disk diameter and the number of disks in the prototype unit would result in a reduction in the solar energy contribution to a value in the range of two or three percent of the total evaporation. Direct solar radiation is a relatively minor consideration in the design of a rotating disk unit.

Comparison of Laboratory and Field Data--

Equations have been developed defining the evaporation rate for the rotating disk unit, based on laboratory studies using the wind tunnel (see Figures 33 and 34). The test conditions included a 2.5 cm (1 in.) disk spacing and wind at 90° to the shaft.

$$E_{(\text{liter/hr}\cdot\text{m}^2)} = (0.0074 + 0.0046\, W_{(\text{kmph})})\, \Delta H_{(\text{gm/kg})}$$

or

$$E_{(\text{gal/hr}\cdot 100\text{ ft}^2)} = (0.018 + 0.018\, W_{(\text{mph})})\, \Delta H_{(\text{lbs/1000 lbs})}$$

Addition of the solar energy term results in the following equations:

$$E_{(\text{liter/hr}\cdot\text{m}^2)} = (0.0074 + 0.0046\, W_{(\text{kmph})})\, \Delta H + 0.88 \quad R_S \frac{A_{vp}}{A_{ws}}$$

or

$$E_{(\text{gal/hr}\cdot 100\text{ ft}^2)} = (0.018 + 0.018\, W_{(\text{mph})})\, \Delta H + 2.1 \quad R_S \frac{A_{vp}}{A_{ws}}$$

The solar energy term utilizes the area relationship, A_{vp} (vertical projecting area) divided by A_{ws} (disk wetted surface area). This ratio was 0.05 for the test unit. The solar energy term R_S is in ly/min.

A comparison of the calculated results with data collected for the unit operating under field ambient conditions is shown in Figure 40. The values calculated from the equations developed from laboratory measurement were slightly lower than the values measured under field conditions. The reason for this was probably due to the nature of the wind velocity. The three-cup anemometer that was used measures only the horizontal component of the wind. In the laboratory wind tunnel the wind direction was essentially horizontal, but under field conditions, some vertical movement of the wind was normal. The coefficients for the evaporation equation adjusted to describe the field ambient measurements are:

$$E_{(\text{liters/hr}\cdot\text{m}^2)} = (0.0074 + 0.005\ W_{(\text{kmph})})\Delta H_{(\text{gm/kg})} + 0.88\ R_S\ \frac{A_{vp}}{A_{ws}}$$

or

$$E_{(\text{gal/hr}\cdot 100\ \text{ft}^2)} = (0.018 + 0.02\ W_{(\text{mph})})\Delta H_{(\text{lbs/1000 lbs})} + 2.1\ R_S\ \frac{A_{vp}}{A_{ws}}$$

Comparison with Evaporation Equations--

Several empirical equations developed for field and lake evaporation have the same general form as those presented for the rotating disk unit. A comparison of the equations is shown below and presented in graphical form in Figure 41 based on the conditions of this study.

Assume: (ΔH = 5 gm/kg and total pressure = 84 kPa)

(ΔH = 5 lb/1000 lb and total pressure = 0.83 atm)

This study - rotating [illegible]vaporator

$$E_{(\text{liter/hr}\cdot\text{m}^2)} = (0.0074 + 0.005\ W_{(\text{kmph})})\Delta H_{(\text{gm/kg})} + 0.88\ R_S\ \frac{A_{vp}}{A_{ws}}$$

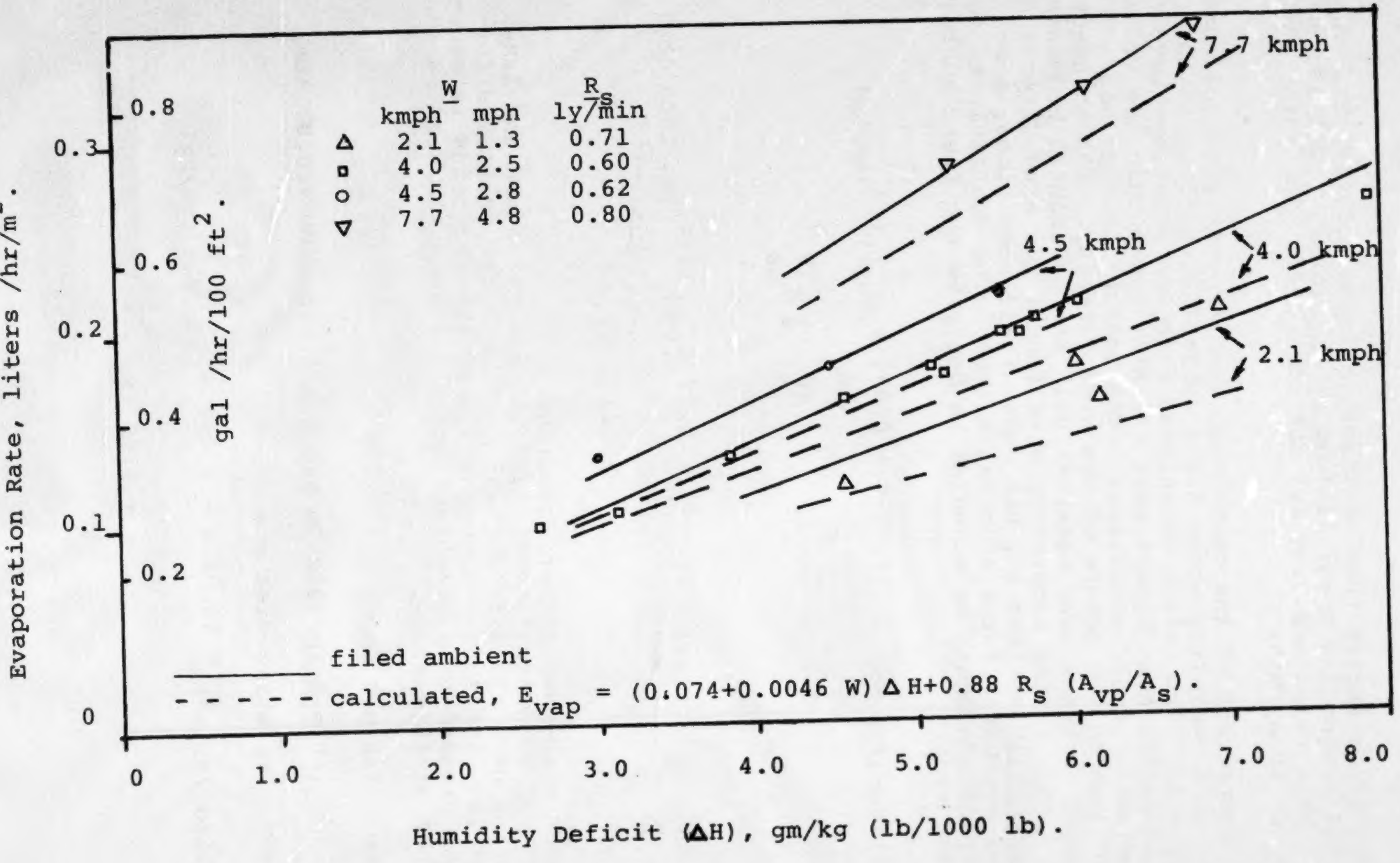


Figure 40. Comparison of actual evaporation to calculated evaporation for the aluminum disk unit receiving solar radiation.

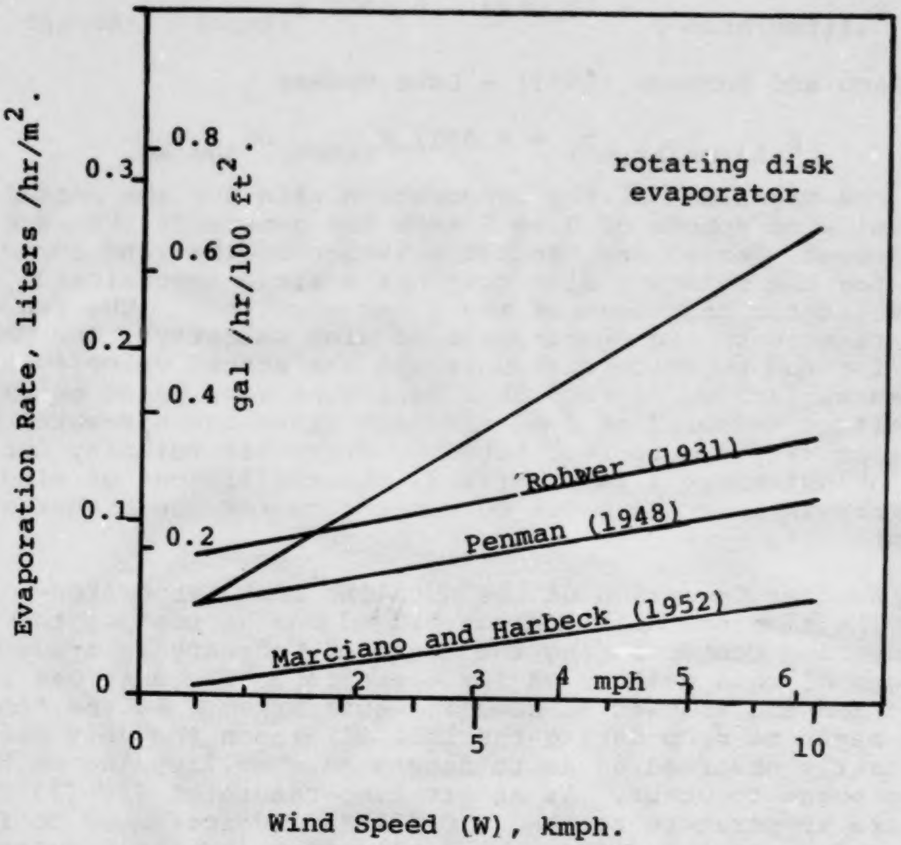


Figure 41. Comparison of RDE evaporation equation with field and lake evaporation equations.

Rohwer (1931) - lakes

$$E_{(\text{liter/hr}\cdot\text{m}^2)} = (0.0154 + 0.0015\ W_{(\text{kmph})})\Delta H_{(\text{gm/kg})}$$

Penman (1948) - small tanks

$$E_{(\text{liter/hr.m}^2)} = (0.0094 + 0.0014\ W_{(\text{kmph})})\Delta H_{(\text{gm/kg})}$$

Manciano and Harbeck (1952) - Lake Hefner

$$E_{(\text{liter/hr}\cdot\text{m}^2)} = 0.0012\ W_{(\text{kmph})}\Delta H_{(\text{gm/kg})}$$

The magnitude of the evaporation rate for the normal ambient wind speeds of 0 to 5 kmph are generally the same using the Rohwer, Penman and the RDE equations. The wind speed function for the rotating disk unit has a slope approximately two times greater than that of the other equations. The reason for this relates to the measurement of wind velocity. The measurement for the rotating disk unit was the actual velocity at the wetted surface while the other equations were based on wind velocities measured at some distance above the air-water interface, usually two to four meters. Since air velocity increases with height above a lake surface, the coefficient of wind velocity is lower in order to compensate for the higher wind measurement.

Cold Weather Operation of the Rotating Disk Evaporator--

The aluminum disk RDE was placed on the roof of the Engineering Center during the month of February to study the effects of cold weather on its operation. The unit was put into operation and allowed to come to equilibrium. As the temperature began to drop during the late afternoon the unit was constantly observed so as to determine when freezing on the disks began to occur. At an air temperature of 4°C (39°F) the mixture temperature reached 0°C (32°F) and ice began to form on the surface of the disks. When allowed to continue operation under freezing conditions, ice completely filled the one inch space between the disks, forming a large, cylindrical ice mass. The thawing of this ice mass took until late afternoon of the following day with high sunlight intensities and temperatures above 10°C (50°F).

An electric submersible tank heater was placed in the tank of the aluminum disk unit to study the efficacy of heating the tank mixture to prevent disk freezing under ambient winter conditions. The 3000 watt heater was equipped with a thermostat control to maintain a constant temperature in the tank. An electric meter was attached to the heater to record total energy consumption. The tank mixture was kept at temperatures of 4°C (39°F) or above, to prevent freezing. The minimum air temperature that occurred during the study was -6°C (21°F). Figure 42

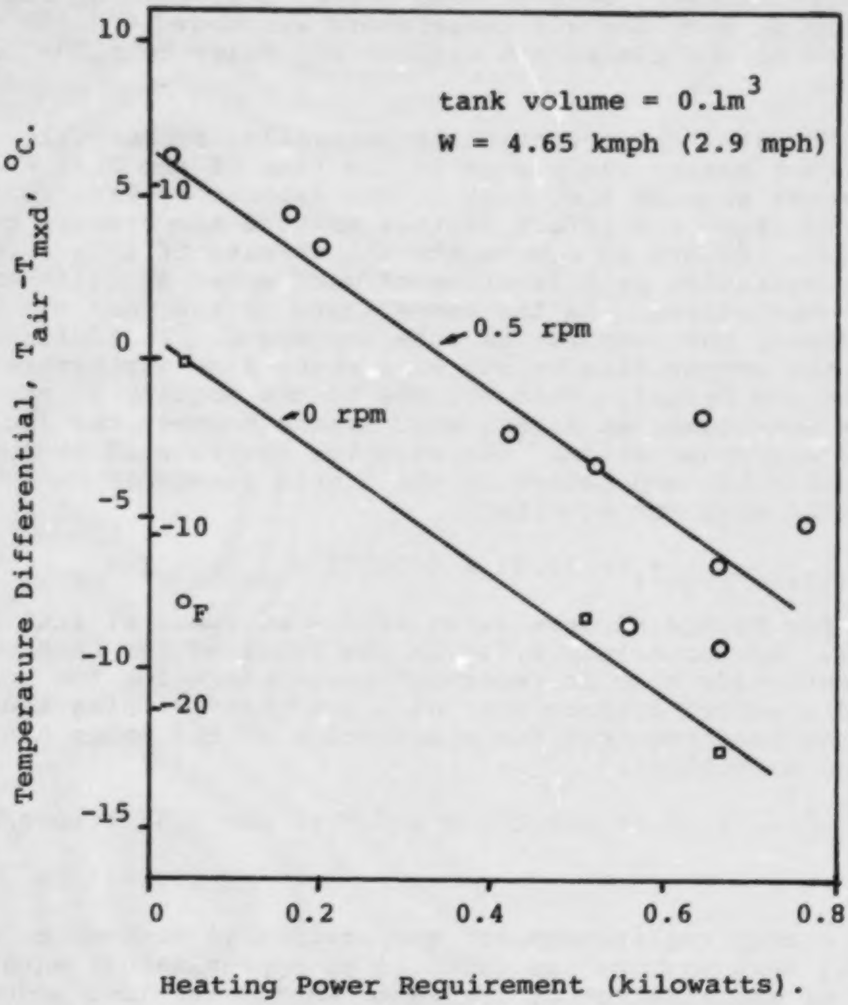


Figure 42. (T_a-T_{mxd}) as a function of power consumed for the aluminum disk unit using a tank heater.

shows the difference in mean air temperature and mixture temperature versus the total power consumed in kilowatts. The figure shows total power consumed for operation of the unit at 0.5 rpm and at 0.0 rpm. A power savings of 0.31 kilowatts was obtained by terminating disk rotation during periods when the air temperature was below 4°C, while using the heater to prevent freezing of the tank mixture. This allowed normal operation of the unit during periods when the air temperature was above 4°C (39°F) without use of the heater and without any delay to allow for thawing.

A 3000 watt, thermostatically controlled submersible electric tank heater was placed in the tank of the 0.91 m (36 in.) diameter plywood disk unit in the laboratory wind tunnel in order to study the effect of tank mixture temperature on evaporation. Figure 43 represents the results of this study by showing evaporation as a function of wind speed at different mixture temperatures. As the temperature of the tank mixture was increased, the evaporation rate increased. In addition, the slope of the evaporation versus wind speed line was greater with the use of the heater. This was due to the ability of the heater to supply more power at higher wind speeds to meet the increased potential for evaporation. The equation for rate of evaporation as a function of temperature in the liquid reservoir can be approximated with the equation

$$E_{(\text{liter/hr.m}^2)} = (0.01 + 0.00075\ W_{(\text{kmph})})\ T_{(^\circ\text{C})}$$

The data for Figure 42 were taken at a wind speed of 4.65 kmph (2.9 mph). Approximately 0.054 KW was required for each one degree centigrade rise in reservoir temperature for the unit which had a wetted surface area of 6.2 meters^2. Using these values, the heat required for evaporation of the water has been calculated as follows:

$$\frac{6.2\ \text{m}^2}{0.054\ \text{KW}/^\circ\text{C}} \times (0.01 + 0.00075 \times 4.65)1^\circ\text{C} = 1.57\ \text{liters/KWH}$$

$$= 550\ \text{cal/gm}$$

The energy requirement for evaporation of wastewater with commercial heat sources was found to be approximately equal to the heat of vaporization of the water when determined under laboratory conditions where heat losses were at a minimum. For outdoor ambient conditions, the energy requirement would be greater.

Using an electrical cost of 4¢/KWH, the cost of wastewater disposal by this method would be 2.5¢/liter (10¢/gal) or more, an unacceptable value. Reservoir heating during freezing weather with the rotating disk unit is not an economically feasible consideration. Heating of the air passing over the disks would also be economically unsound. It appears that the best method

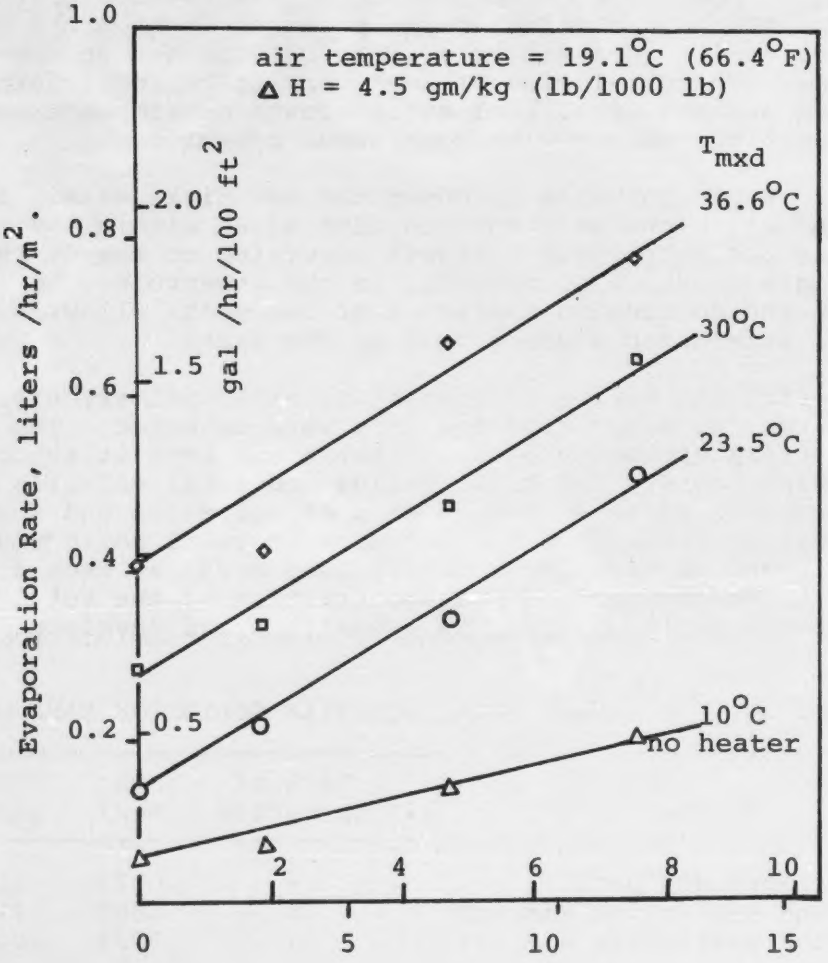


Figure 43. Evaporation as a function of wind speed at various tank mixture temperatures. Data taken from 36.0 inch dia. plywood disk unit.

of operation would be to terminate operation and drain the unit when the ambient air temperature drops below 4°C (39°F) and to fill and operate the unit when the temperature rises again. This operation will require a storage vault capable of holding the wastewater flow through the maximum freezing weather period.

Continuous Operation of the Rotating Disk Evaporator--

The RDE with aluminum disks pictured in Figure 3 was operated during June and July under outdoor ambient conditions to assess the correlation of long term operational data with recorded weather data, biological growth development on the disks and possible problems with continuous operation.

Algae growth began to cover the end disks within the first week and all disks were covered with algae within six weeks. This was the only visible growth occurring on the disks. Extensive algae growth also occurred in the reservoir. An interruption in the continuous operation of the unit, allowing the disk to dry, eliminated algae growth on the disks.

During the period of operation, using primary clarified wastewater, no odors from the unit were detected. The rotation of the disks aerated the tank mixture and kept it aerobic, thus preventing odors. The total solids and total volatile solids were measured after 30 and 37 days of operation and the results are shown in Table 10. The increase in total solids and total volatile solids was approximately 1000 mg/ℓ per week and 100 mg/ℓ per week, respectively. A large fraction of the total solids and total volatile solids was algae that had developed in the tank.

TABLE 10. TOTAL AND TOTAL VOLATILE SOLIDS OF TANK MIXTURE

Sample	Days of Operation	TS mg/ℓ	TVS mg/ℓ
Primary effluent	-	329	127
Tank wastewater mixture	30	4008	918
Tank Wastewater mixture	37	5038	1022

Comparison of Actual and Computed Evaporation--

The design of a rotating disk evaporator for a specific location involves applying values of mean weekly or monthly weather parameters in the evaporation equation. To determine the validity of using mean monthly or weekly values, a comparison between actual evaporation and computed evaporation was made for data collected during the operation of the aluminum disk unit under field conditions. The resllts are shown in Table 11. It can be seen that the actual evaporation from the unit was

TABLE 11. COMPARISON BETWEEN ACTUAL AND COMPUTED EVAPORATION USING MEAN MONTHLY AND MEAN WEEKLY WEATHER PARAMETERS

From	To	Δt hr	Ꝟ_d ℓ	T_a ^oC	r.h. %	ΔH gm/kg	W kmph	R_s ly/min	E_{actual} mm/hr	E_{comp} mm/hr	E_{pan} mm/hr
5/31	7/5	819.75	689.01	25.3	36.7	4.10	3.7	0.333	0.13	0.12	0.29
5/31	6/7	175.75	163.26	26.1	29.4	4.85	3.2	0.357	0.14	0.13	0.32
6/30	7/5	131.00	132.00	26.5	36.0	4.49	4.0	0.344	0.16	0.14	0.34

wetted area = 6.6 m^2

E_{comp} = computed evaporation = $(0.0074 + 0.005\ W)\Delta H + 0.88\ R_s \dfrac{A_{vp}}{A_{ws}}$

Ꝟ_d = volume evaporated over the time period slightly greater than the value computed from the equation. The evaporation rate per unit of wetted area for the unit was found to be about 0.44 times that of the rate measured using the standard class A pan at the same location.

The comparison of disk evaporation per unit area with pan evaporation was made for many of the short term tests that were used in the study of operating variables. This correlation is shown in Figure 44. The effect of sunlight is greater in pan evaporation because solar radiation strikes the total wetted surface. The effect of wind speed is also different for air moving between the disks and air moving over the water surface in the pan. In spite of these differences, the correlation in the figure is relatively good and gives a value for disk evaporation per unit wetted area of 0.42 times the pan evaporation, a figure very similar to that derived from long term data.

Investigation of Health Hazards and Odors--

No objectionable odors were detected in the air exiting the wind tunnel during operation of the rotating disk evaporators in the laboratory wind tunnel. Primary effluent was used during these studies. The rotation of the disks sufficiently aerated the wastewater to prevent it from becoming anaerobic and producing odors. When the unit was stopped for more than 24 hours, odors began to develop. This problem can be eliminated by draining the unit when not in use or by operating the drive mechanism for at least a short period each day.

The possibility that wind blowing over the rotating disk may contain bacterial aerosols which would present a health hazard was recognized and a brief evaluation was made. Two types of tests for coliforms were made. In one test, a membrane filter apparatus was set up at several distances, 0.15 m, 1.5 m and 3 m (0.5 ft, 5 ft and 10 ft) from the downwind edge of the rotating disks. Air was drawn through the filter while the unit was operating. After a period of operation, the membrane filters were applied to total coliform media and incubated. The second test involved the use of membrane filters in dishes containing total coliform media placed at the same distances from the unit. During operation, aerosol falling from the air passing over the disks could drop onto the filters. After designated periods of operation, the filters were incubated and counted.

No coliforms were measured at any of the distances using the first technique. The second method produced coliform measurements immediately adjacent to the unit at 0.15 m (0.5 ft) but not at greater distances. The results are shown in Table 12.

From this preliminary testing, it can be concluded that bacterial transport in aerosols is not a serious health problem.

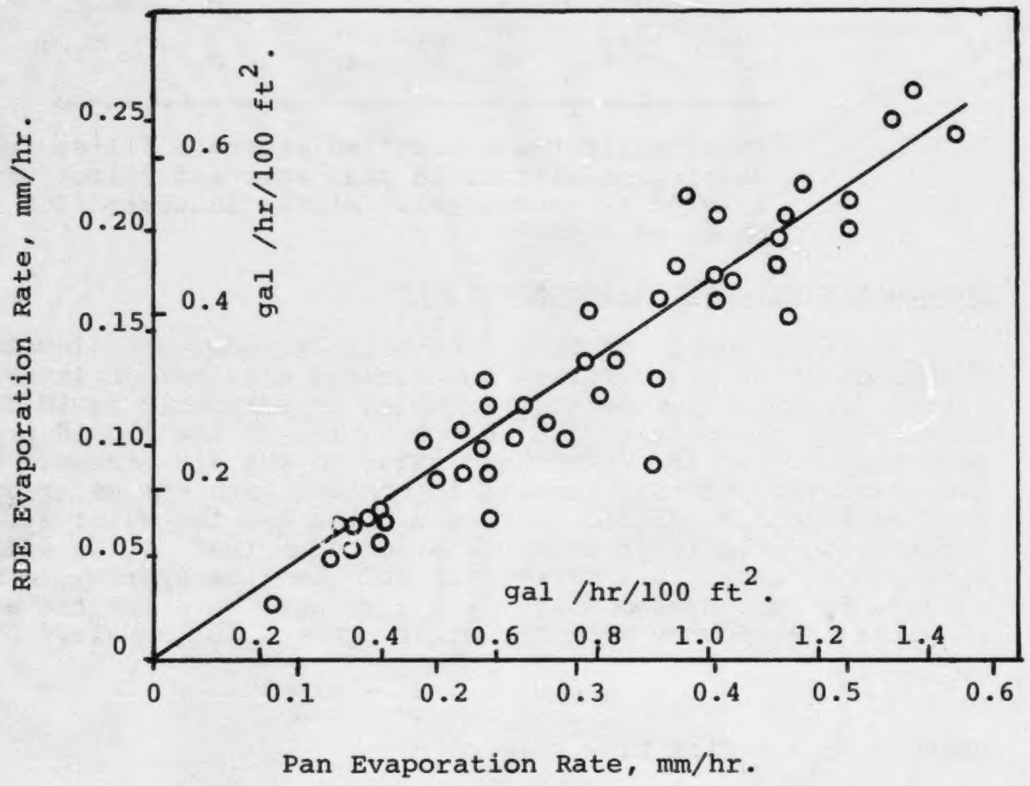


Figure 44. Evaporation as a function of pan evaporation for the aluminum disk unit.

TABLE 12. RESULTS OF MODIFIED TOTAL COLIFORM MEMBRANE FILTER TESTS

Δt hr	W kmph	Total Coliforms[a] Blank	0.15 m	1.5 m	3 m
1.0	3.1	0	5	-	-
2.5	3.1	0	27	-	-
2.0	3.1	0	20	0	0
2.25	7.6	0	2	0	0
2.0	12.2	0	0	0	0
1.0	7.6	0	4	0	0

[a] Total coliforms - modified membrane filter test, petri dish with media pad, agar and filter exposed to wind at tank level. Dishes incubated for 24 hours at 37°C.

Concentric Cylinder Evaporator (CCE)

The functioning of the concentric cylinder unit involves the movement of pressurized, unsaturated air through layers of wetted burlap. The operation results in adiabatic humidification and cooling of the air with heat transfer to the liquid producing mass transfer of the evaporated water to the air stream. During the adiabatic process, the air in contact with the water surface will exit in a condition near saturation and the water surface temperature will reach an equilibrium near that of the adiabatic saturation temperature of the air entering the system. A mass balance for the system will yield a relationship for the amount of water transferred from the water surface to the air.

$$\dot{m} H_i = \dot{m} H_o - w$$

where $\dot{m}$ = Mass flow rate of air

H_i, H_o = Humidity of air in and out of system, respectively

w = Mass rate of evaporation

For the adiabatic process, the mass rate of evaporation can be expressed as

$$w = \dot{m} \Delta H_2$$

This equation can be rearranged to the form:

$$E_c = K'Q\rho\Delta H_2$$

where E_c = Evaporation from CCE, ℓ/hr or gal/hr

K' = Conversion constant

Q = Volumetric flow rate of air, ℓ/hr or ft^3/hr

ρ = Density of air, kg/ℓ or lb/ft^3

ΔH_2 = Adiabatic humidity deficit of air entering unit, gm/kg or lb/1000 lb

The equations are based on an isolated system with the only heat entering or leaving the system being associated with the piped air flow. In the operation of the test unit, two other sources, the ambient air flowing over the cylinder and solar radiation on the cylinder, had a small but significant effect. These sources were accounted for by adding terms to the evaporation equation.

Mixture Temperature--

The relationship between the bulk mixture temperature and the adiabatic saturation temperature of the supply air for the concentric cylinder unit operating under both field and laboratory conditions is shown in Figure 45. The mixture temperature was within 3°C of the adiabatic saturation temperature of the supply air for most cases and therefore the adiabatic humidity deficit accurately describes the water vapor gradient above the water surface.

Air Flow Rate--

The evaporation rate from the concentric cylinder unit was directly proportional to the mass or volumetric flow rate of the supply air entering the unit. The relationship between evaporation from the concentric cylinder unit operating under laboratory conditions and the air flow rate at different adiabatic humidity deficits of the air supply is shown in Figure 46. Since the unit was exposed to the ambient air of the laboratory, there was a small evaporation rate from the wetted fabric surface at zero air flow rate.

Adiabatic Humidity Deficit--

The mass balance equation presented previously was based on the assumption that, as the air passed through the saturated fabric, it was saturated with water vapor. Evaporation was therefore assumed to be directly proportional to adiabatic humidity deficit. The evaporation rate as a function of adiabatic humidity deficit for the concentric cylinder unit operated at four different air flow rates in the laboratory is shown in Figure 47. The evaporation rate is shown as a linear function of adiabatic humidity deficit. The intercept of the curve is slightly above the origin due to a small effect of the ambient air passing over the surface of the cylinder.

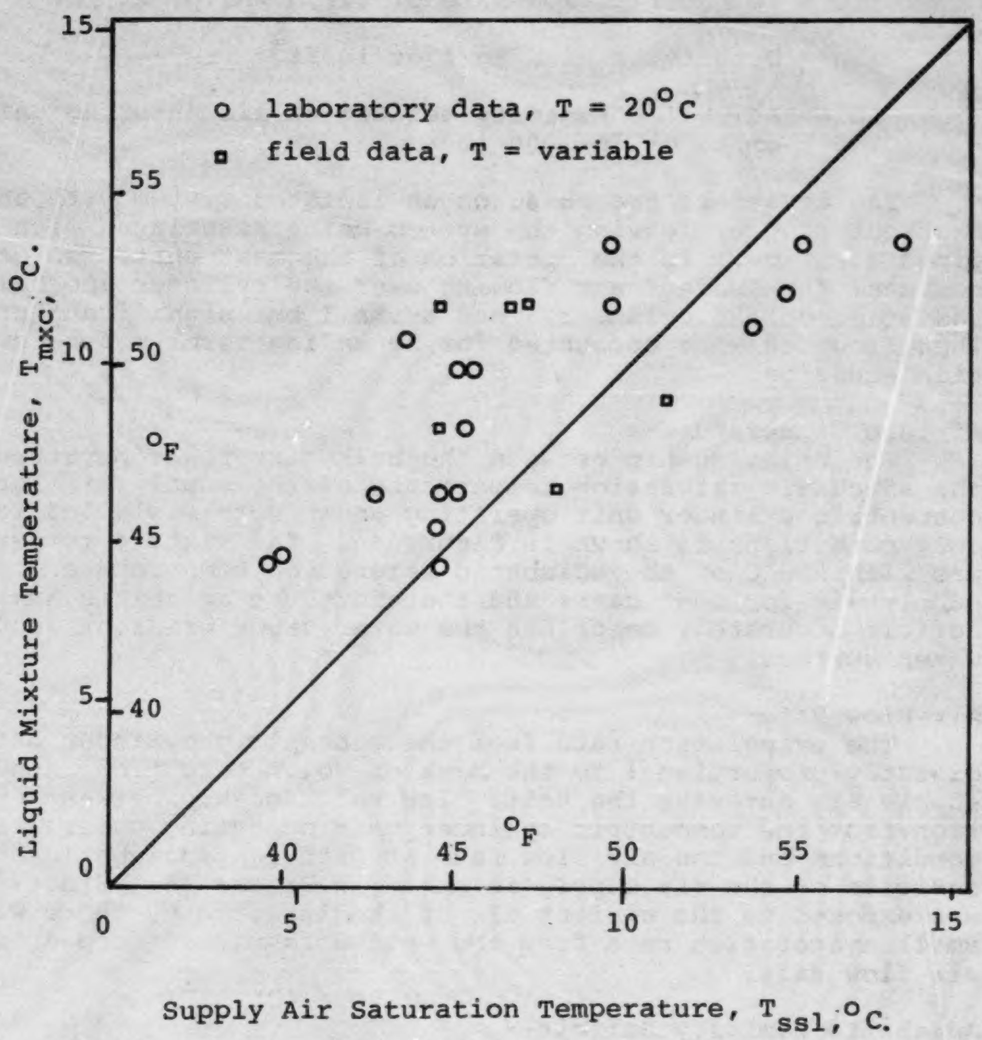


Figure 45. Concentric cylinder unit bulk mixture temperature as a function of the adiabatic saturation temperature of the supply air.

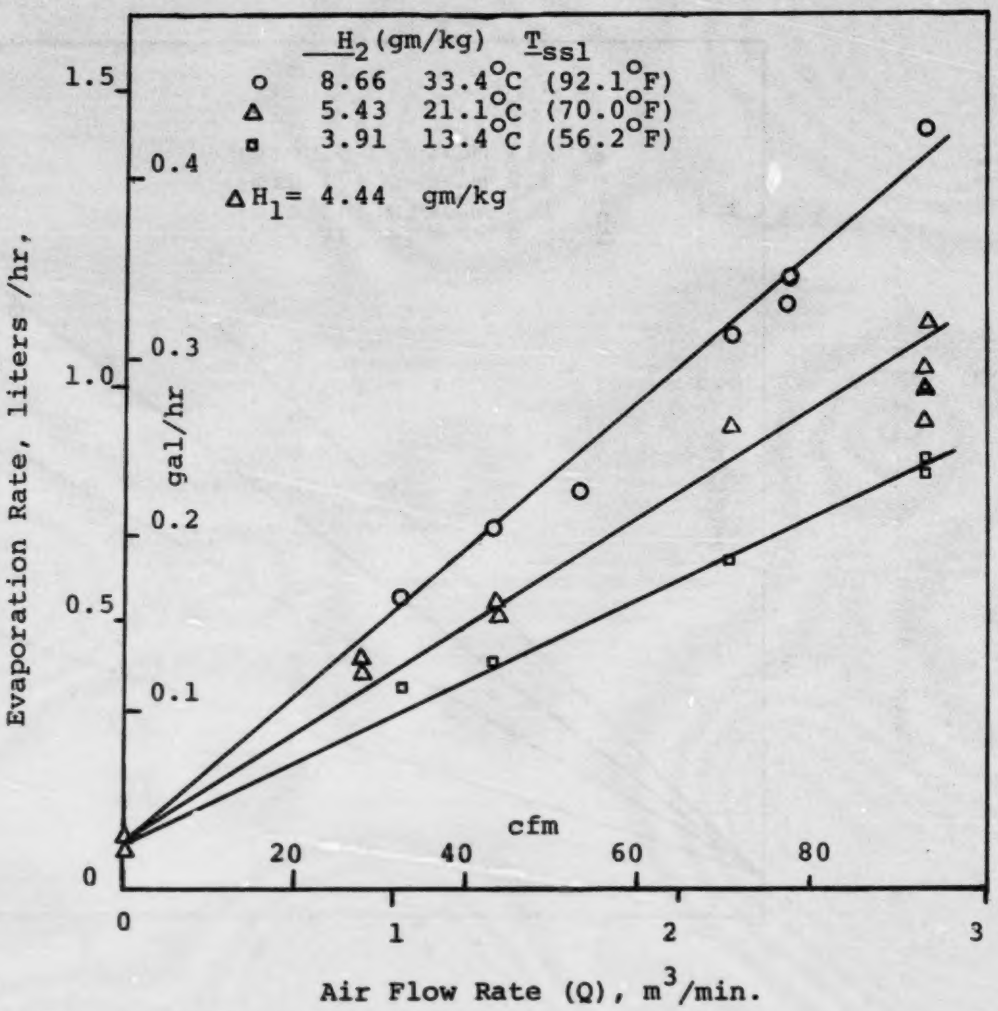


Figure 46. Evaporation as a function of air flow rate at different supply air himidity deficits for CCE in the laboratory.

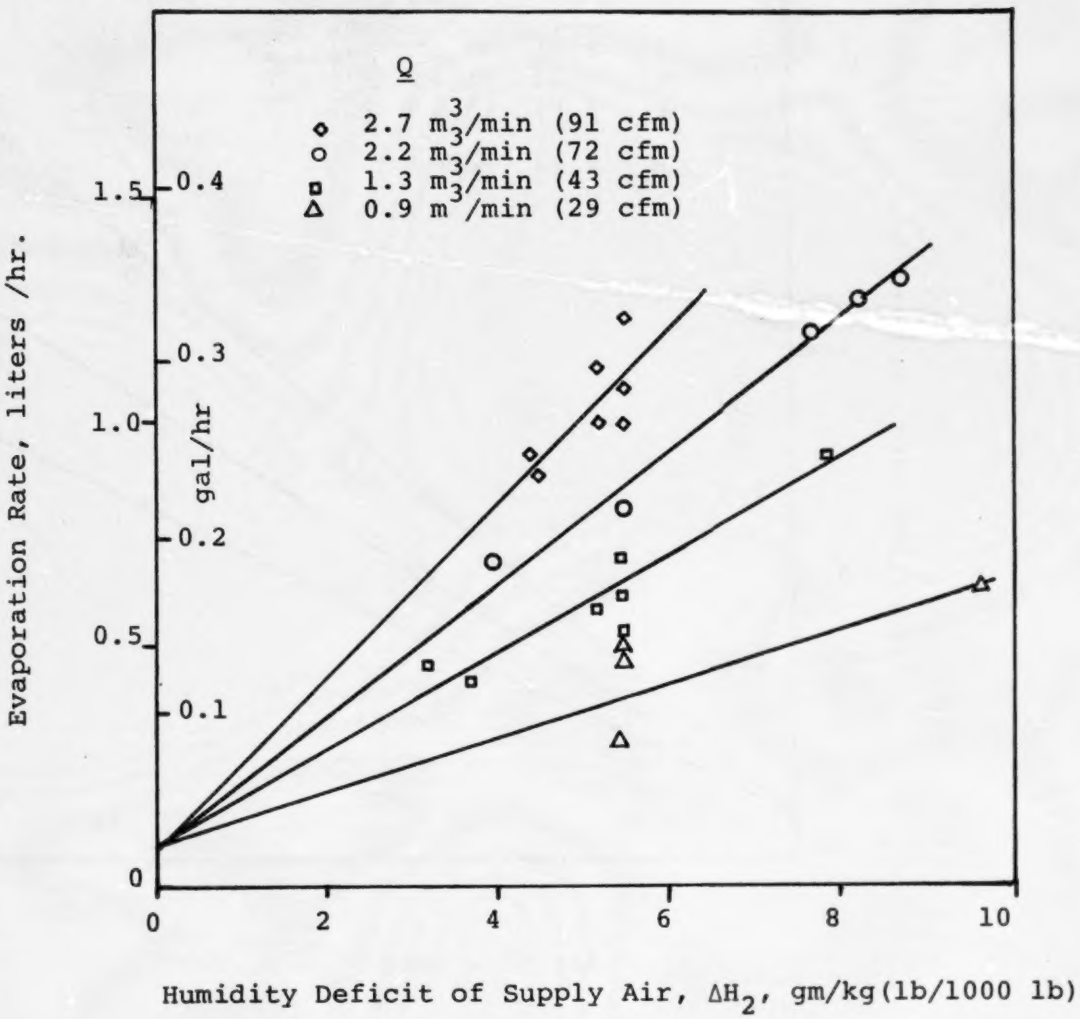


Figure 47. Evaporation as a function of adiabatic humidity deficit of supply air for CCE in the laboratory.

The major variables influencing evaporation from the concentric cylinder unit have been shown to be the flow rate and humidity deficit of the air piped into the system. The equations relating these variables were established from the slope of the lines in Figures 46 and 47.

$$\text{(S.I. units)} \quad E_c\ (\ell/\text{hr}) = 0.0684\ Q_{(m^3/\text{min})}\, \Delta H_{2\,(\text{gm/kg})}$$

$$\text{(Engl. units)} \quad E_c\ (\text{gal/hr}) = 0.00055\ Q_{(\text{cfm})}\, \Delta H_{2\,(\text{lb}/1000\ \text{lb})}$$

The effect of the other factor influencing evaporation rate, the ambient air speed, humidity deficit, and direct solar radiation were investigated in order to provide a more complete equation describing system performance.

Effect of Wind on Evaporation from CCE--

The concentric cylinder unit was operated in the laboratory wind tunnel at three different piped air flow rates, three different ambient air wind speeds, and a single adiabatic humidity deficit of the supply air in order to determine the effect of ambient wind speed on evaporation. The relationship between evaporation and wind speed is shown in Figure 48. The increase in evaporation was the same for each air flow rate at a constant ΔH_2. The increase can be expressed as

$\Delta E/W = 0.0165$ liters/hr·kmph, for the unit

$\Delta E/W = 0.007$ gal/hr·mph, for the unit

at a $\Delta H_2 = 5.49$ gm/kg (lb/1000 lb). The exposed wetted fabric area was 0.7 m^2 (7.2 ft^2), making the ratio of $E/W = 0.024$ $\ell/\text{hr}\cdot m^2\cdot$kmph (0.001 gal/hr·$ft^2$·mph). The assumption has been made that the effect of wind speed is directly proportional to ΔH_1. This was found to be true with the rotating disk unit and is incorporated in the field evaporation formulas presented in the previous sections. On this basis, the effect of wind speed becomes, $\Delta E = 0.005\ \Delta HW$ when using SI units, and $\Delta E = 0.0002\ \Delta HW$ for English units.

Effects of Ambient Air Humidity Deficit--

The adiabatic humidity deficit of the surrounding air will affect evaporation from the surface of the outer cylinder. The mixing of the saturated supply air and the ambient air at the surface of the outer cylinder causes an increase in the water vapor gradient at the surface which affects evaporation.

To show the effects of the surrounding air under constant operating conditions, the cylinder was fitted with a cover constructed from one-half of a 55 gallon drum. The cover matched the reservoir and fitted snugly over the unit except for a slot that allowed the air to escape. The cover prevented ambient air

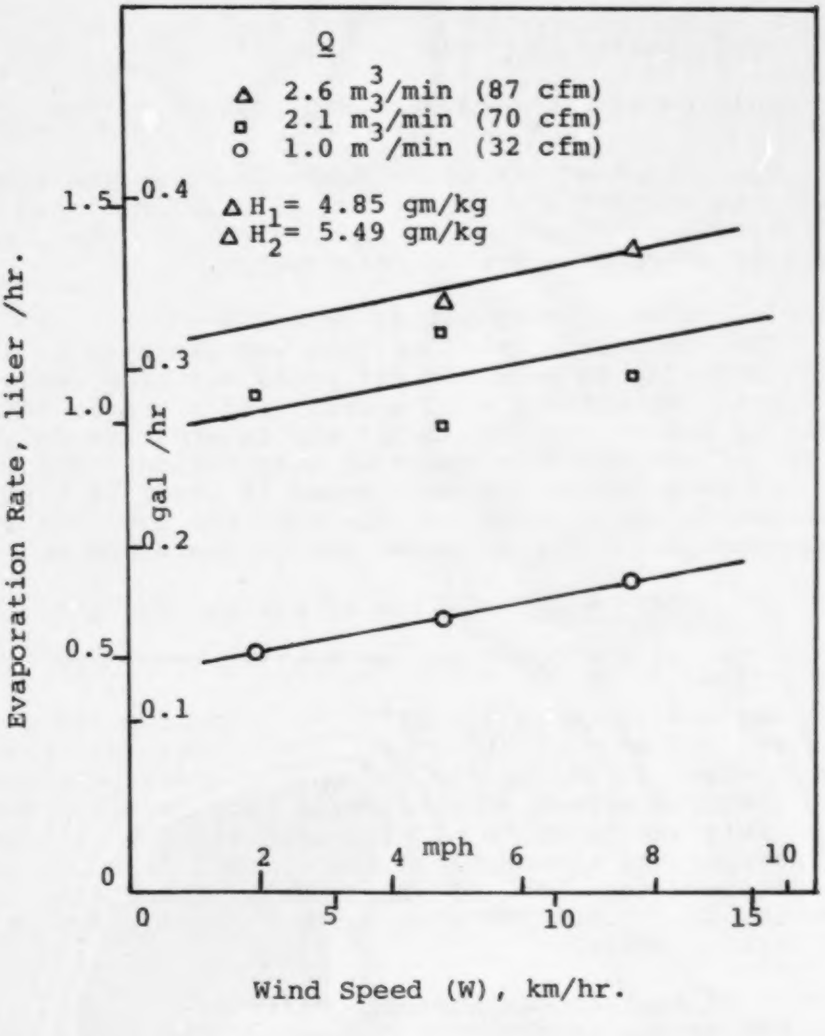


Figure 48. Evaporation as a function of wind speed for CCE unit in the laboratory wind tunnel.

from contacting the cylinder. Data from an open unit and a covered unit were plotted as shown in Figure 49. The evaporation from the open unit was consistently higher than evaporation from the covered unit. The amount of increased evaporation from the open concentric cylinder unit appeared to be a constant under laboratory conditions.

Ambient wind movement in the laboratory studies was less than one km/hr and therefore the increase in evaporation with the uncovered unit is considered to be due to the humidity deficit of the ambient air. It has been shown, for the piped air of the concentric cylinder unit and the ambient air of the disk unit, that evaporation is proportional to humidity deficit. The average evaporation at zero wind speed was approximately 0.1 ℓ/hr·unit at an ambient air humidity deficit of 4.4 gm/kg. This results in a value of 0.032 $\ell/\text{hr}\cdot\text{m}^2\cdot\Delta H$ or (0.008 $\text{gal}/\text{hr}\cdot\text{ft}^2\cdot\Delta H$) to be used in the evaporation equation.

Effect of Solar Radiation--

Direct solar radiation absorbed by the moist outer surface of the cylinder adds energy to the system that results in increased evaporation. Several determinations of evaporation rate were made outdoors under field conditions during daylight hours in the summer. Data for two different solar radiation intensities were selected where all other operating variables were essentially constant. Solar radiation was measured with a recording pyranometer and the units of measurement are Langleys/min ($\text{cal}/\text{cm}^2\cdot\text{min}$). A plot of the data is shown in Figure 50. The dashed lines are from calculated data without the effect of solar radiation.

$$\text{(S.I. units)} \quad E_c = A_S(0.032 + 0.005\ W)\Delta H_1 + 0.0684\ Q\Delta H_2$$

$$\text{(English units)} \quad E_c = A_S(0.0008 + 0.0002\ W)\Delta H_1 + 0.00055\ Q\Delta H_2$$

where A_S = exposed, wetted surface area, 0.7 m^2 for the test unit.

The evaporation due to direct solar radiation measured from the curve is 0.46 ℓ/hr at an R_S of 0.69 Ly/min and 0.10 ℓ/hr at 0.14 Ly/min or

$$\text{(S.I. units)} \quad \Delta E_{vap} = 0.67\ R_S = 0.96\ A_S R_S$$

$$\text{(English units)} \quad \Delta E_{vap} = 0.18\ R_S = 0.025\ A_S R_S$$

The unit evaporated an average of 460 gm of water due to a solar radiation of 0.69 ly/min x 60 min/hr x 0.7 m^2 x 10^4 cm^2/m^2 = 289,800 calories, or 630 cal/gm of H_2O. The water temperature was 12°C. At that temperature, the heat of vaporization of water

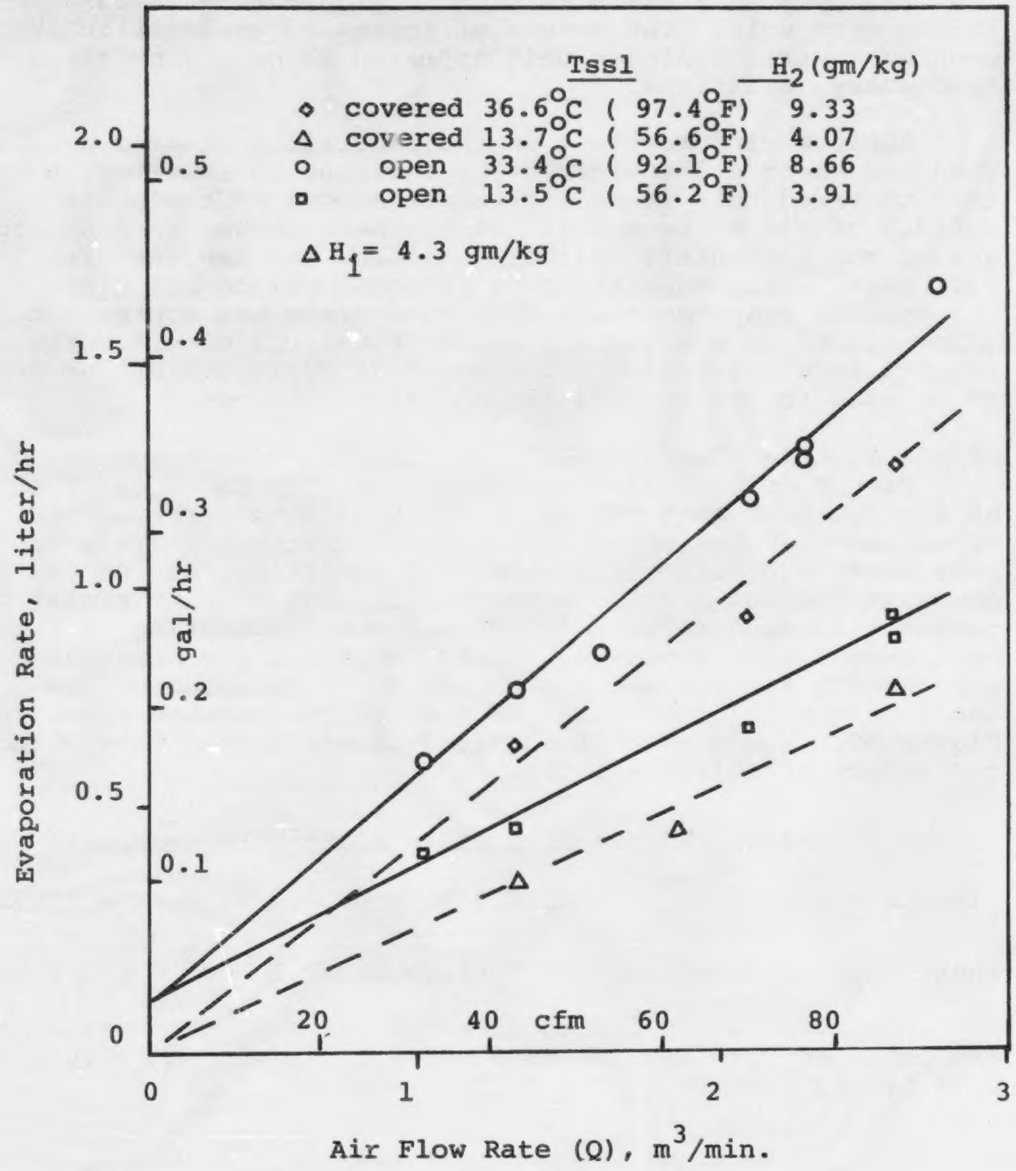


Figure 49. Evaporation as a function of piped air flow rate for a covered and an open CCE operating in the laboratory.

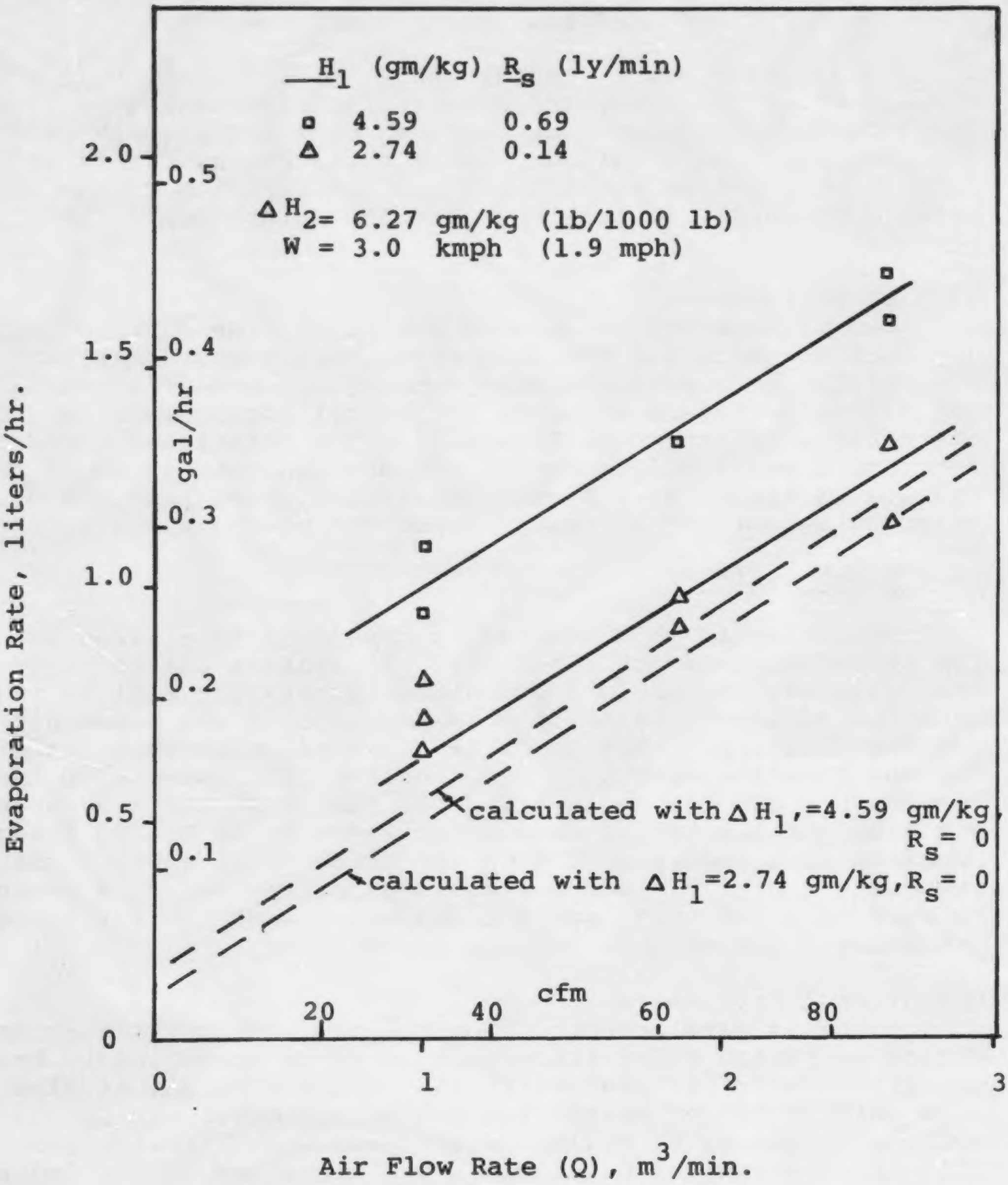


Figure 50. Evaporation as a function of piped air flow rate for the CCE operating under field ambient conditions.

is approximately 590 calories/gm. The reflected solar radiation was apparently about six percent which is within the range to be expected for a dark colored, rough fabric surface.

From Figure 50, it appears that solar radiation is a significant source of energy for evaporation with this type of unit. The data for the figure was obtained during the sunny portion of a summer day. On a full day, year round basis, direct solar radiation is not as significant and the capacity of the unit is related primarily to the flow rate and saturation deficit of the piped air.

Machine Variables--

Two machine variables were evaluated, the depth of submergence of the drum and the drum rotational speed. Maximum evaporation rate occurred when submergence was great enough to wet all three layers of wraps in the cylinder. This is shown in the results presented in Figure 51. The rotational speed of the drum had a small effect on the evaporation rate as shown in the results in Figure 52. Higher rotational speed kept the cloth slightly wetter and increased vapor transfer a small amount.

Cold Weather Effects

Operation in cold weather is dependent to a large extent on the temperature of the piped air. If ambient air is piped into the cylinder, the minimum operating temperature will be reached when the adiabatic saturation temperature of the piped air reaches freezing. This condition is similar to that described for the rotating disk unit and freezing will occur when the air temperature reaches 4° to 5°C. The test unit utilized pressurized air from the laboratory at a temperature of 20°C. No freezing problems were encountered with operation at an ambient air temperature of 1°C. Lower ambient temperatures could probably be used with the unit, but 1°C was the lowest ambient temperature encountered during this portion of the study.

Operational Problems--

No odors were detected from the concentric cylinder unit during operation under laboratory or field conditions. Primary clarified municipal wastewater was used during all studies. A dark mold developed on the surface of the outer burlap cloth cylinder. The cloth easily decayed and lost its strength. Any attempt to clean the outer cloth was unsuccessful and led to its replacement. No pore clogging problems were encountered with respect to the inner cylinders. The inner cloth did begin to decay, but not as rapidly as the cloth on the outer surface. For a prototype unit, a fabric would be required which can resist corrosion and be easily cleaned. A stainless steel or synthetic fiber fabric could be used.

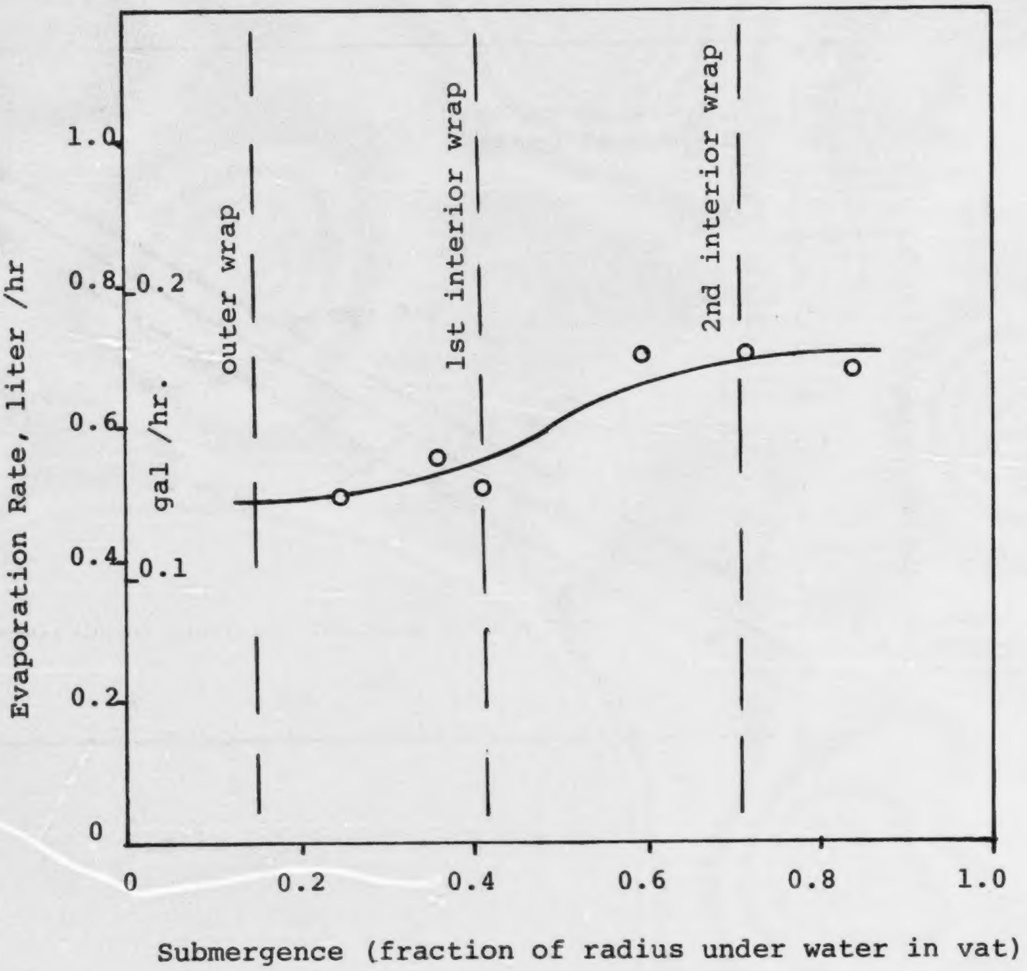


Figure 51. CCE evaporation as a function of submergence.

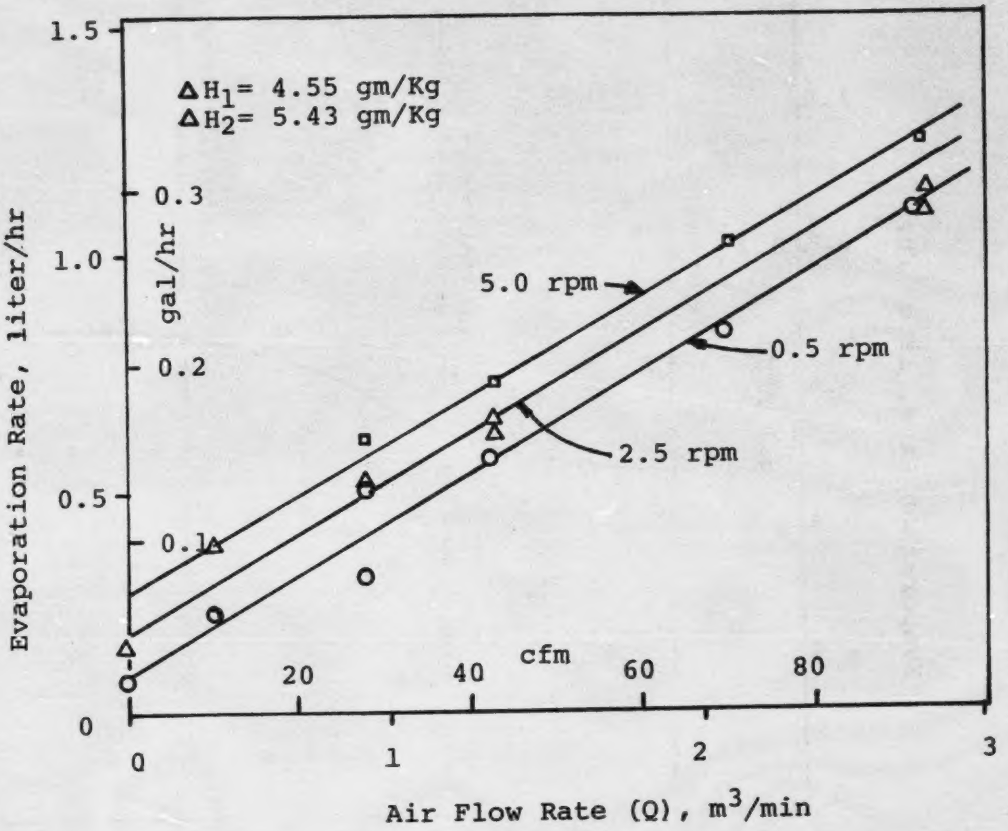


Figure 52. Evaporation as a function of air flow rate at different rotational speeds for the CCE operating in the laboratory.

Equations for Evaporation Rate from the CCE--

The machine variables have a very small effect on the performance of the unit. For a cylinder submergence great enough to wet the inner fabric wraps and a rotational speed of about one or two RPM, the expression developed in this section based on air flow rate Q (m^3/min, cfs), supply air humidity deficiency ΔH_2 (gm/kg, lb/1000 lb), ambient air humidity deficiency ΔH_1 (gm/kg, lb/1000 lb) and solar radiation R_S (ly/min), adequately describe the process.

$$\text{(S.I. units)} \quad E_c \quad (\ell/\text{hr}) = A_S(0.032 + 0.005\ W)\Delta H_1 + 0.0684\ Q\Delta H_2 + 0.96\ A_S R_S$$

$$\text{(English units)} \quad E_c \quad (\text{gal/hr}) = A_S(0.0008 + 0.0002\ W)\Delta H_1 + 0.00055\ Q\Delta H_2 + 0.025\ A_S R_S$$

It should be noted that the evaporation rate equations above describe the evaporation rate of the total unit. If these relationships are divided by the area of the outer burlap surface covering, A_S, an expression similar to that of the RDE equations results and evaporation, E_{vap}, is expressed as a function of a unit area of the burlap surface.

$$\text{(S.I. units)} \quad E_{vap} \ (\ell/\text{hr}\cdot\text{m}^2) = (0.032 + 0.005\ W_{(kmph)})\Delta H_1 + 0.0684\ \frac{Q}{A_S}\frac{(m^3/min)}{(m^2)}\Delta H_2 + 0.96\ R_S$$

$$\text{(English units)} \quad E_{vap} \ (\text{gal/hr}\cdot 100\ \text{ft}^2) = (0.08 + 0.02_{(mph)})\Delta H_1 + 0.055\ \frac{Q}{A_S}\frac{(cfm)}{(ft^2)}\Delta H_2 + 2.5\ R_S$$

Only one size concentric cylinder evaporator was used in the studies and therefore the use of the above equations for designing a larger prototype unit, with a larger value of A_S, was not experimentally verified.

SECTION 8

DESIGN METHODS, NATIONAL APPLICATIONS AND COSTS

EVAPOTRANSPIRATION BED DESIGN

The design criteria for an ET bed are highly site specific and take into account as major considerations the water use pattern in the home, acceptance criteria, and local weather parameters.

The water use pattern can be estimated based on the type of facility. For a single family home, a flow of 170 liters (45 gallons) per person per day has been established, resulting in a design flow rate per dwelling unit, based on five occupants per home, of 850 liters (225 gallons) per day. Although some minor daily and seasonal variations occur, this flow rate can be assumed to be constant throughout the year. The use of water saving appliances and plumbing devices can reduce the design flow by one-third. Because of the direct cost savings realized with reduced ET bed size, these devices should be considered in the design of any ET system. Use of water saving devices result in a reduced design flow of 600 liters (150 gallons) per day for a house. Flow estimates based on the number of bedrooms in a house tend to result in overestimates for flows from large homes. Apparently, the number of bedrooms in a home and the number of potential occupants is not closely correlated.

An attractive application of evaporative systems is for installations where flow rates are higher during the summer months. These systems take advantage of the higher evaporative potential available in warm weather. Wastewater disposal for summer homes, many types of recreational areas, and highway rest areas are some of the examples of this application. Generally, summer home flow rates are similar to those of permanent homes except that the period of use is limited to the summer months. Other applications are based on the specific conditions of the site use; consequently the flow rate must be established for each individual installation.

Variations in acceptance criteria produce a wide range of design values and sometimes makes it difficult to compare design loading rates for different areas. If the acceptance criteria are based on a totally evaporative, non-discharging system, the loading rate must be low enough that the bed never completely fills, assuming that all precipitation enters the unit and does not run off. This is the criteria that was used in the evaluation of loading rate for the lysimeter studies in this report. The acceptance criteria may allow for lateral or vertical seepage in conjunction with evaporation. The design loading rate for the combination concept can be considerably higher and the incremental increase is dependent upon the allowable seepage rate. The acceptance criteria may allow occasional surface runoff during precipitation events as long as nuisance conditions do not result. This approach will generally result in increases in loading rate of fifty to one hundred percent above that for the non-discharging system. The acceptance criteria are usually set by local health authorities to accommodate the needs of a particular area. The requirements to be met for an isolated farm home in a rural area may be quite different from those for homes in suburban subdivisions. The non-discharging criteria may be required in the latter case where the homes are in relatively close proximity, expecially if well water supplies are involved. Higher loading rates and less demanding criteria may be acceptable for the more rural applications.

The weather parameters are major considerations in the design of an ET system. These include precipitation and evaporation rate data. Rainfall and snowfall measurements are available from NOAA for thousands of weather stations throughout the country. Many local agencies also maintain records. A critical wet year should be used for design based on at least ten years of records.

Establishing evaporation data at a specific location can be a more difficult problem. Measurements of class A pan evaporation are reported for all of the states by NOAA in the publication, "Climatological Data", U.S. Department of Commerce available in repository libraries for government documents at major universities in each state. Pan evaporation measurements are made at a few (five to thirty) weather stations in each state. Data for the winter months is often omitted because this method cannot be used under freezing weather conditions. The critical period of the year for design of ET units for permanent homes is in the winter. Establishing representative winter evaporation data is probably the most difficult part of ET bed design analysis. The application of ET beds is most favorable in the warm dry climates of the southwestern U.S. For these areas, pan evaporation data are available for the complete year. The analysis of evaporative potential for cooler, semi-arid regions such as eastern Washington and Oregon, Utah, Colorado and similar areas requires that winter data be established by means other than pan evaporation measurements since these data are generally not available.

One method for establishing representative winter evaporation data is to take measurements on buried lysimeters in a manner similar to that used in this study. Another method is to use the empirical formulations such as the Penman formula or others. Most of the empirical formulas were developed for calculating evaporation during the growing season and may not apply directly to winter circumstances. It was found in this study that the Penman formula did give results comparable to the measured winter values. A graphical method has been reported by Dalinsky (1975) that utilizes the sinusoidal nature of solar radiation to give monthly evaporation patterns. Based on studies in Israel, he noted that the mean evaporation for the year was of the same magnitude as that measured for the months of April or October and that the monthly variations form a sine curve with a maximum in July and a minimum in January. For most locations, data is available for the months of April, July and October. Using the April/October data as the annual average, the additional amplitude in July can be subtracted from the average to establish the minimum value in January. If the April/October evaporation rate is 5 mm/day and the July rate is 8 mm/day, the estimated January value would be 5 - (8-5) = 2 mm/day. Ward (1977) has illustrated the use of this technique for Denver, Colorado. In general, the method gives reasonably good correlations for the portion of the U.S. that is east of the Rocky Mountains but it does not appear to be applicable in western states where weather is influenced by the mountainous topography.

After the precipitation and evaporation curves for an area have been established, the design is based on an allowable liquid loading rate per unit of surface area. Based on the data established during the study period, the allowable loading rate for year round operation of a non-discharging system in the study area was found to be 1.6 mm/day (0.04 gpd/ft^2). This is shown in the shaded portion of Figure 53, which was constructed from the data in Table 6. This is the same value as that established in the more detailed experimental study. This analysis was presented to show that, in this case, the use of monthly weather data provides results that concur with those of the detailed experimental lysimeter studies. The allowable loading value was established, based on the proven assumption that an ET system has very limited storage capacity, and therefore the evaporation rate in the winter months must be great enough to remove all entering wastewater and precipitation. In addition, winter evaporation rates from an ET bed are nearly equal to the measured evaporation values from pan or lysimeter measurements.

Based on the evaporation rates established in this way, the size of ET bed required for a non-discharging system in a permanent home without flow reduction devices would be $(850 \times 10^{-3}$ m^3/day)/$(1.6 \times 10^{-3}$ m/d) = 530 m^2 or 5700 ft^2. This is approximately the size of the home ET beds in use in the Boulder area. The value of 1.6 mm/d was established on the basis of a single winter of study during a period when a drought condition existed. The amount and distribution of precipitation are quite variable throughout a long period in any given area. In order to assess

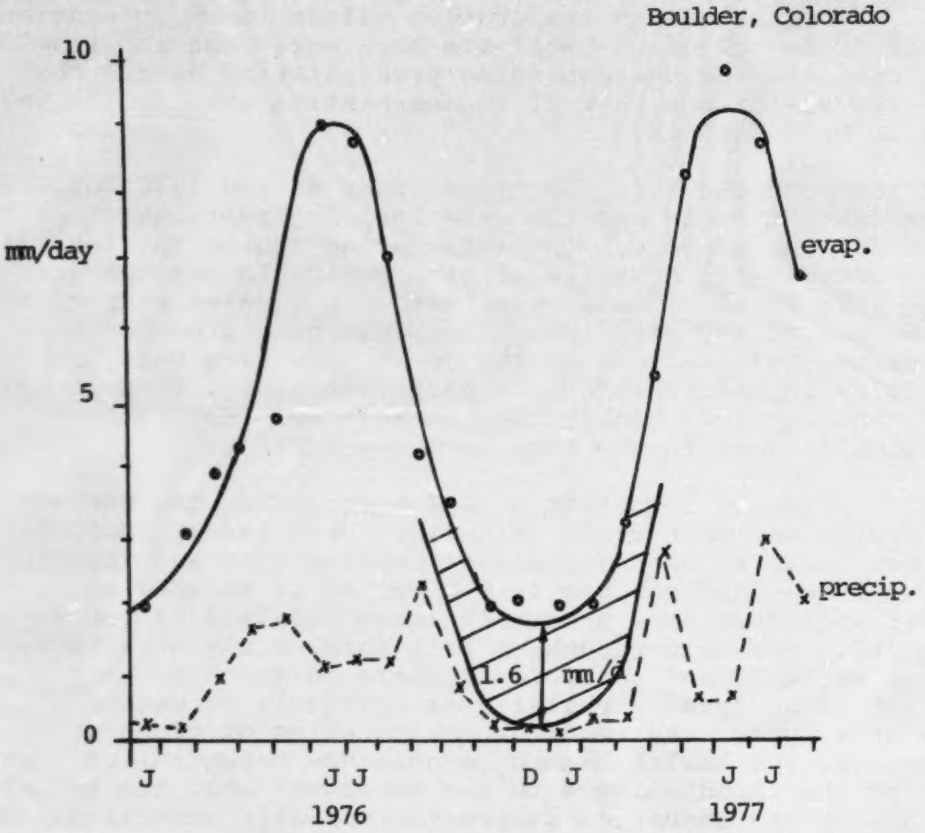


Figure 53. Curve for establishing permanent home loading rate for Boulder, Colorado based on winter data 1976-1977.

the influence of changing weather conditions, the monthly rainfall patterns should be evaluated for at least the previous ten years. This analysis for the Boulder, Colorado study area is shown in Figure 54. It would be desirable to have measured evaporation values for each month of each year. Evaporation data is so difficult to establish, especially in the winter months, that this was not possible. The measured values for the 1976 study were used for each of the years in the figure. In general, the reported pan evaporation values for most stations listed in "Climatological Data" are much more constant from year to year than are the corresponding precipitation data. For this reason, the use of one year of representative evaporation values appears to be justified.

It can be noted from the figure that during 1976 Boulder was in a drought cycle and the data does not represent a critical year for design purposes. The late spring storms in 1969, 1970 and 1971 provide the most restrictive period in the ten year sequence. In April of 1971, precipitation equaled evaporation and an ET bed of any practical size would have produced some runoff during that period. Although ET beds have been used successfully in the area for the past five years, this location must be considered as highly questionable for truly non-discharging systems in the long term application.

This raises an important question regarding the concept of ET bed design and acceptance criteria. Very large precipitation events can occur at very infrequent intervals at any location. ET beds are designed for use over a period of decades and therefore will encounter some unusually large rainfall or snowfall occurrences. For this reason, a fail safe, truly non-discharging system is probably not possible anywhere in the U.S. A precise definition of acceptance criteria is difficult to establish. Failure of a system may involve contamination of groundwater from seepage, the health hazard or nuisance potential of surface runoff, or the inconvenience to the homeowner when the system cannot accept the amount of wastewater normally generated. The relationship between these conditions and the weather variables used in design can only be established with long experience with actual systems.

The use of ET systems for summer homes is a very attractive application in the western states of the U.S. A much smaller bed is required and the cost becomes more competitive with leaching fields and other alternatives. It can be determined from Figure 54 that 1967 is the critical year of the ten year period for summer evaporative conditions. A graph of these data, as shown in Figure 55, is used to establish a design wastewater evaporative rate of 4 mm/d (0.10 gpd/ft) for the case of summer home design where only the months of June, July and August are considered. ET bed evaporation rate has been shown to be only about 75-80 percent of the pan evaporation rate in the summer

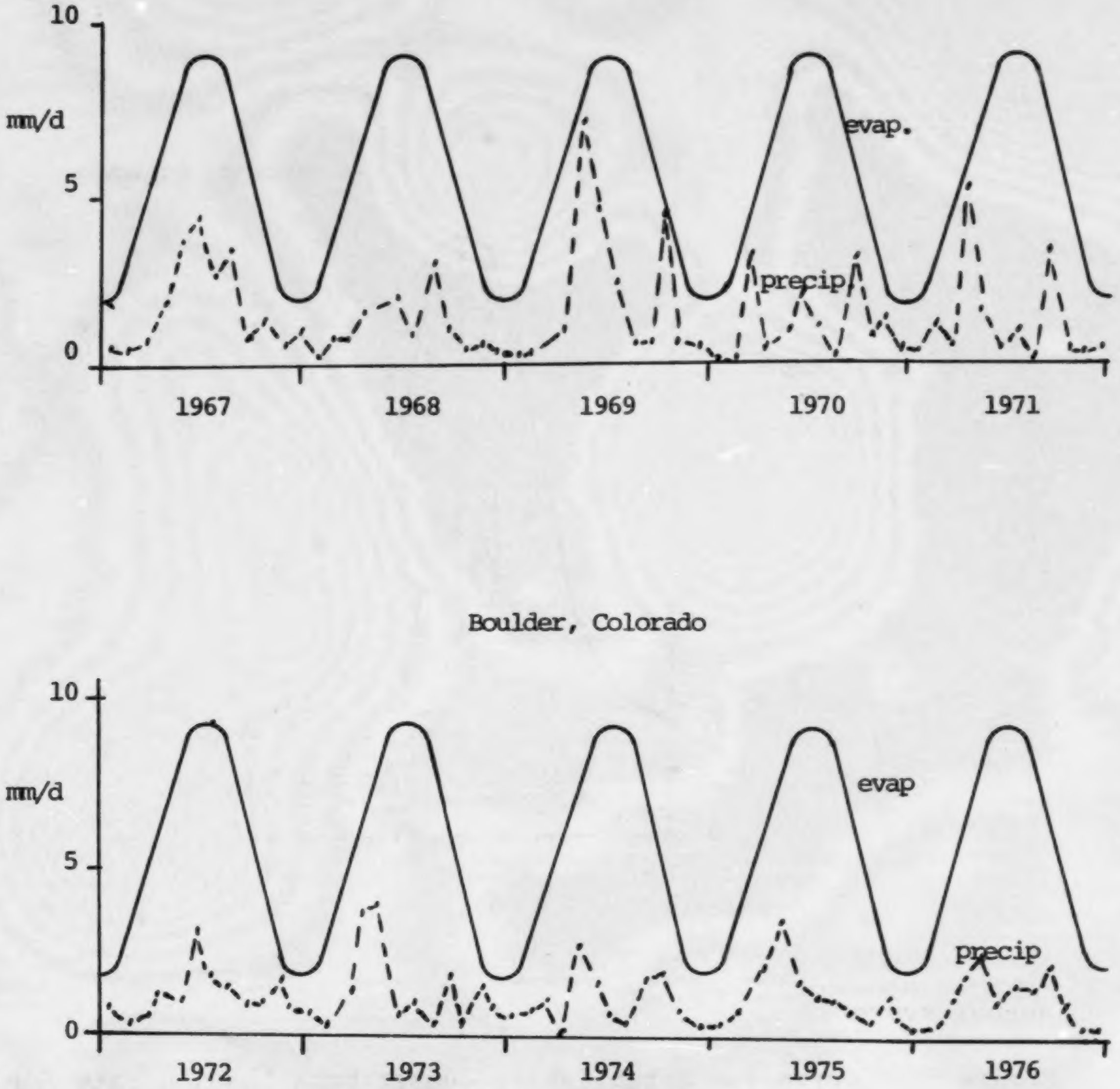


Figure 54. Ten year evaporation and precipitation pattern for Boulder, Colorado.

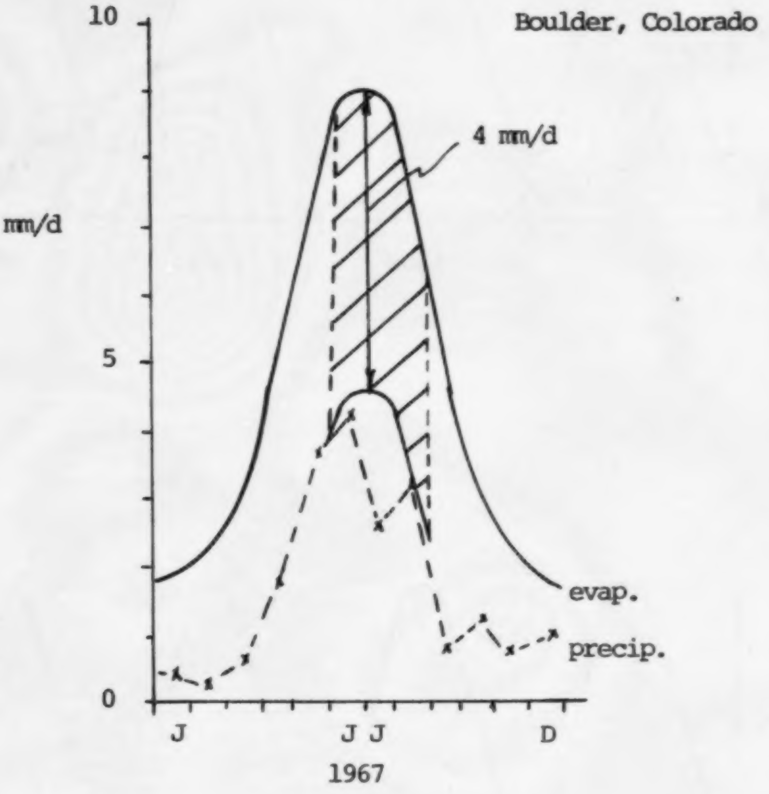


Figure 55. Curve for establishing summer home loading rate for Boulder, Colorado based on critical year data of 1967.

months. On this basis, the required bed size for summer home application in the study area would be $(850 \times 10^{-3}\ m^3/d)/(4 \times .8 \times 10^{-3}\ m/d) = 265\ m^2$ or 2850 ft^2 without the use of water saving appliances, or 175 m^2 (1900 ft^2) or less if water conservation is practiced.

NATIONAL APPLICATIONS OF ET SYSTEMS

The use of ET beds for year round application for permanent homes can be assessed from plots of the weather variables for different locations in the nation. This provides only a general overview and individual analyses must be made at each potential site based on localized weather data and acceptance criteria. Several locations were selected throughout the country and plots are presented that represent the critical precipitation year from a ten year span from 1967 to 1976. Data for the figures were obtained for each state from the NOAA publication "Climatological Data".

The data for three locations in the eastern U.S., southern Florida, northern Georgia and upstate New York are shown in Figure 56. It can be noted that in all of these locations, there were several months when precipitation exceeded evaporation. The use of non-discharging ET systems would not be acceptable for either permanent homes or summer residences at these locations. Combination seepage and evaporation systems would function primarily as seepage units with only a small fraction of the water disposal due to evaporation. A similar situation exists in the midwestern states as shown in Figure 57.

The application of ET systems in the intermountain valleys between the western coastal mountains and the eastern front range of the Rockies is much more favorable. The high plains adjacent to the eastern edge of the Rocky Mountains is an area with evaporation exceeding precipitation in all months of the year as shown in Figure 58. The concept of using ET units for permanent homes is applicable for some limited areas of Wyoming, Colorado and New Mexico, although the required size of beds may be quite large. The use of ET systems for summer home installations would be acceptable. The weather data for several other eastern areas are shown in Figures 59, 60 and 61. El Paso, Texas is one of the most arid places in the U.S., but it is subject to quite infrequent, very high intensity storms. One such storm occurred during the analysis period in 1974. If it were not for the September 1974 rainfall, the analysis would show that this area would allow one of the highest loading rates for ET systems in the country. This is an example of the considerations that must be taken into account with acceptance criteria. Saltair, Utah shows very marginal conditions for December, January and February of the critical precipitation year. Fallon, Nevada is an example of another very arid region of the U.S.

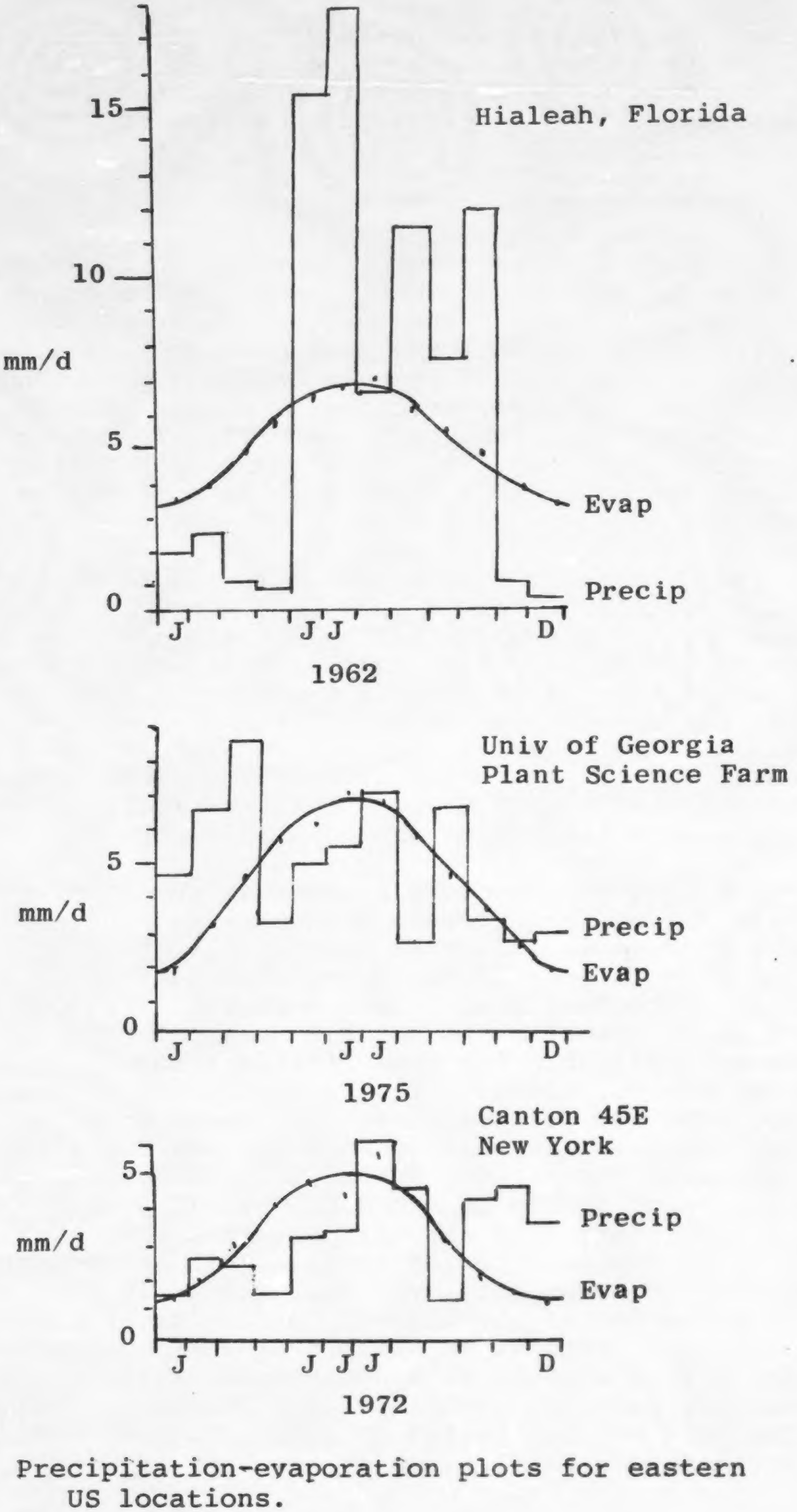


Figure 56. Precipitation-evaporation plots for eastern US locations.

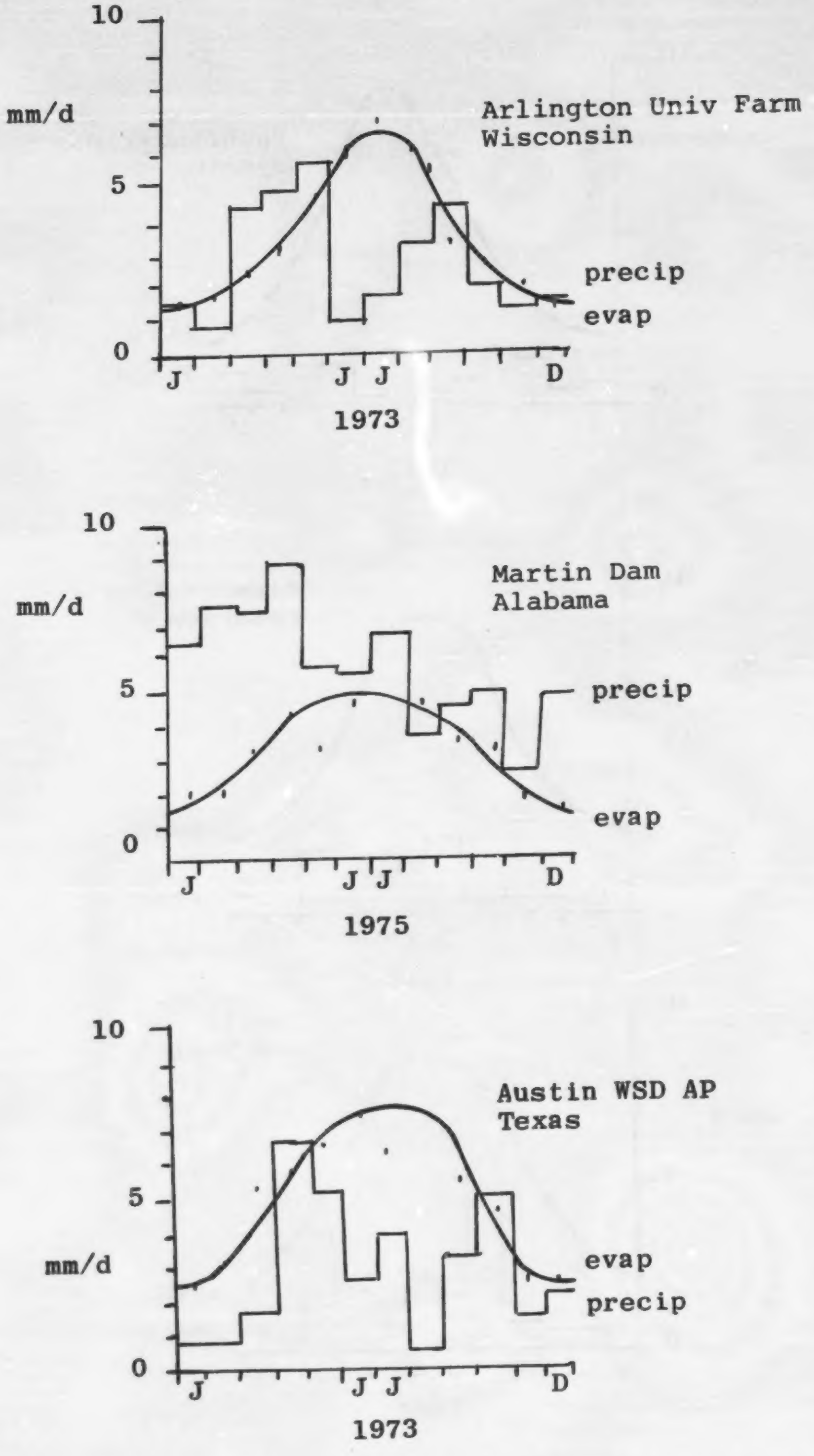


Figure 57. Precipitation-evaporation plots for midwest locations.

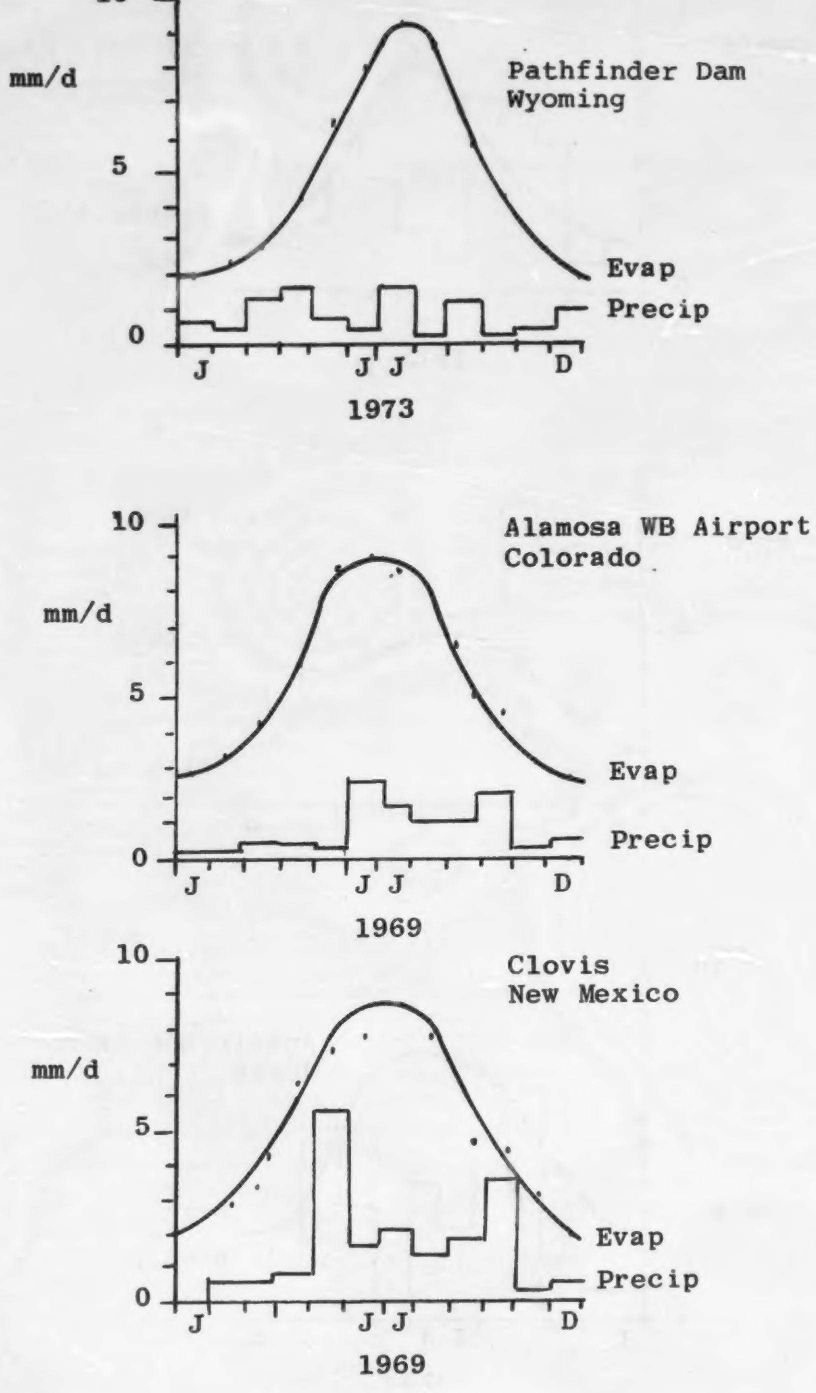


Figure 58. Precipitation-evaporation plots for Rocky Mountain locations.

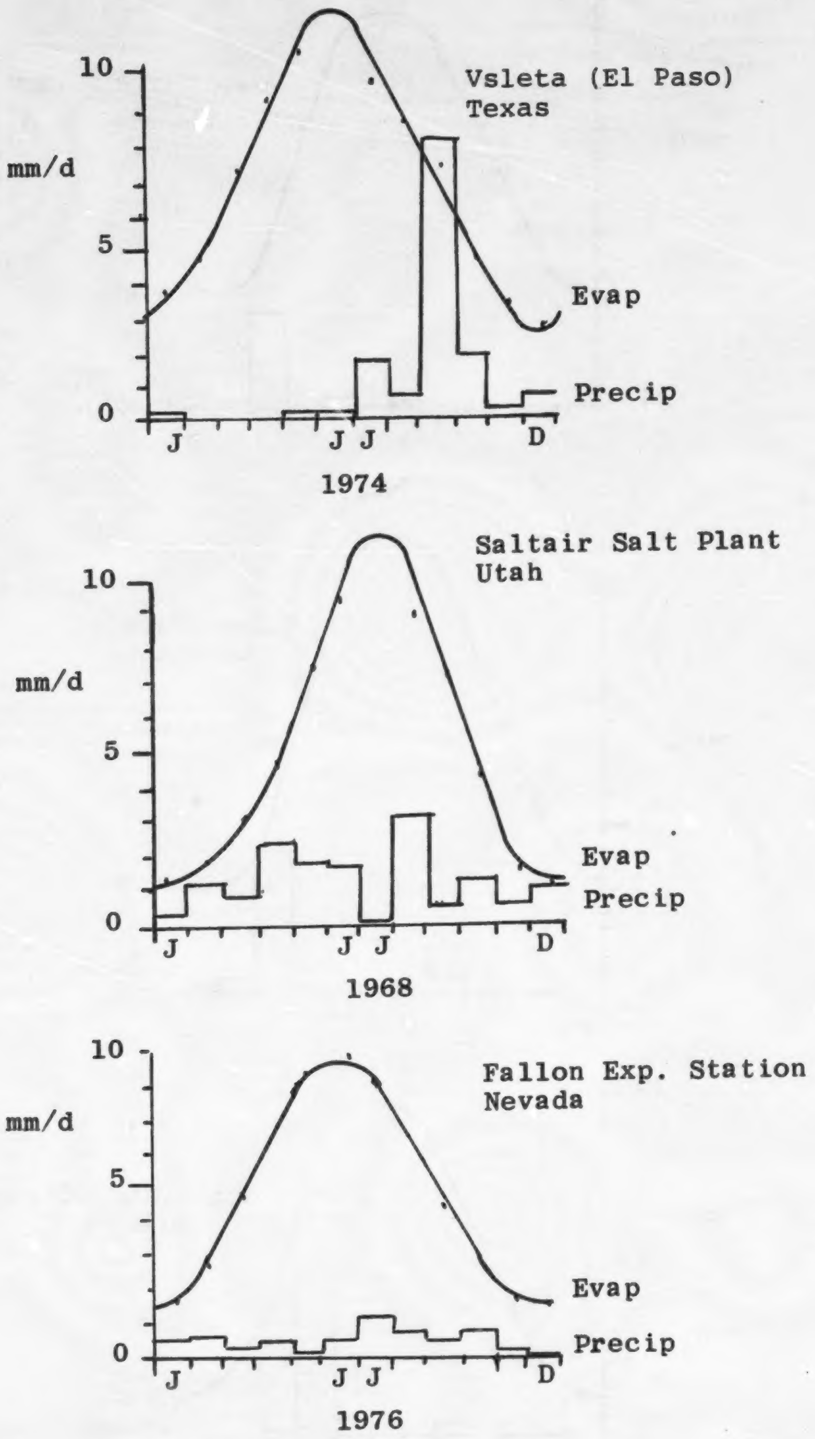


Figure 59. Precipitation-evaporation plots for intermountain locations.

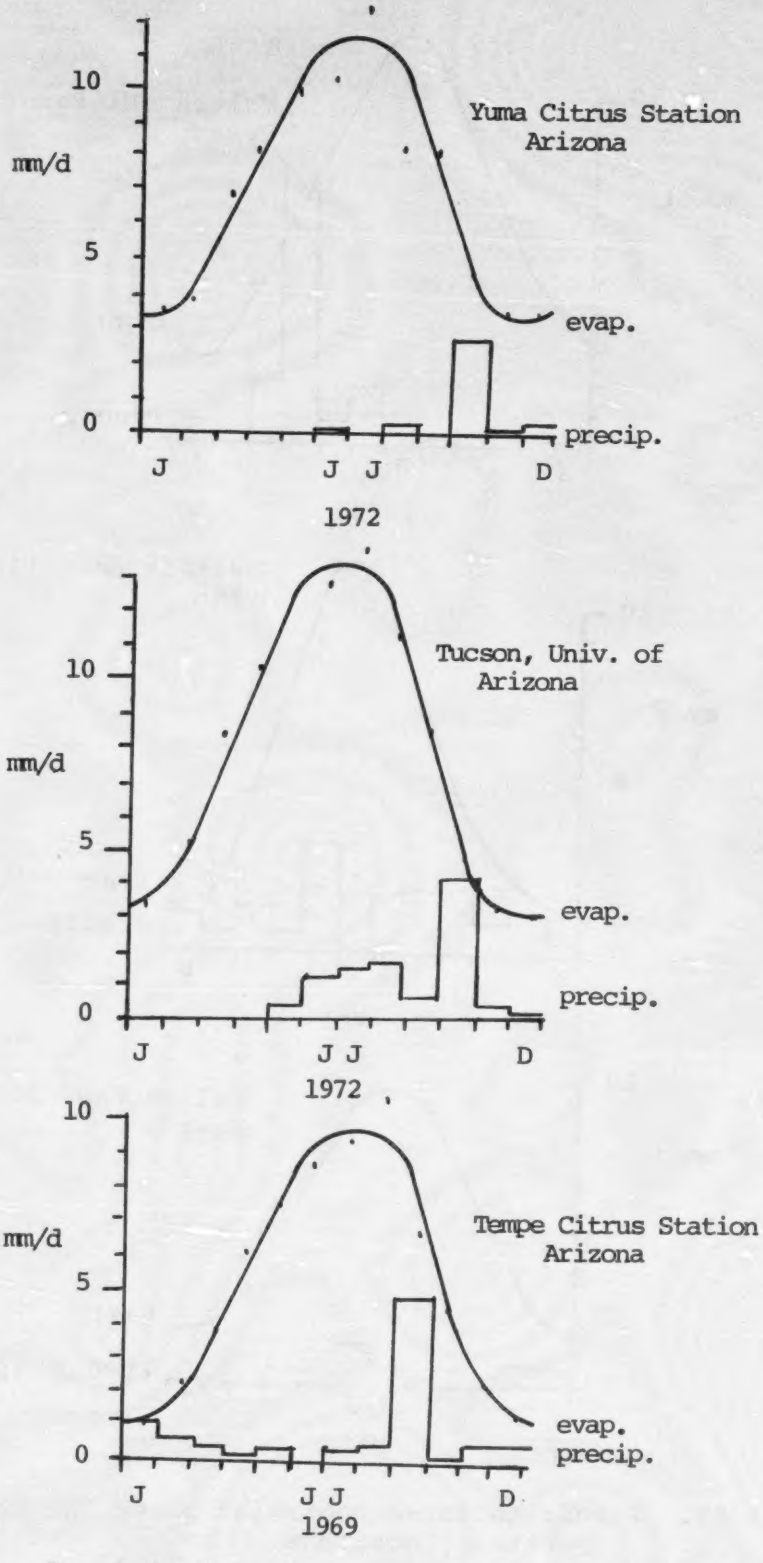


Figure 60. Precipitation-evaporation plots for Arizona locations.

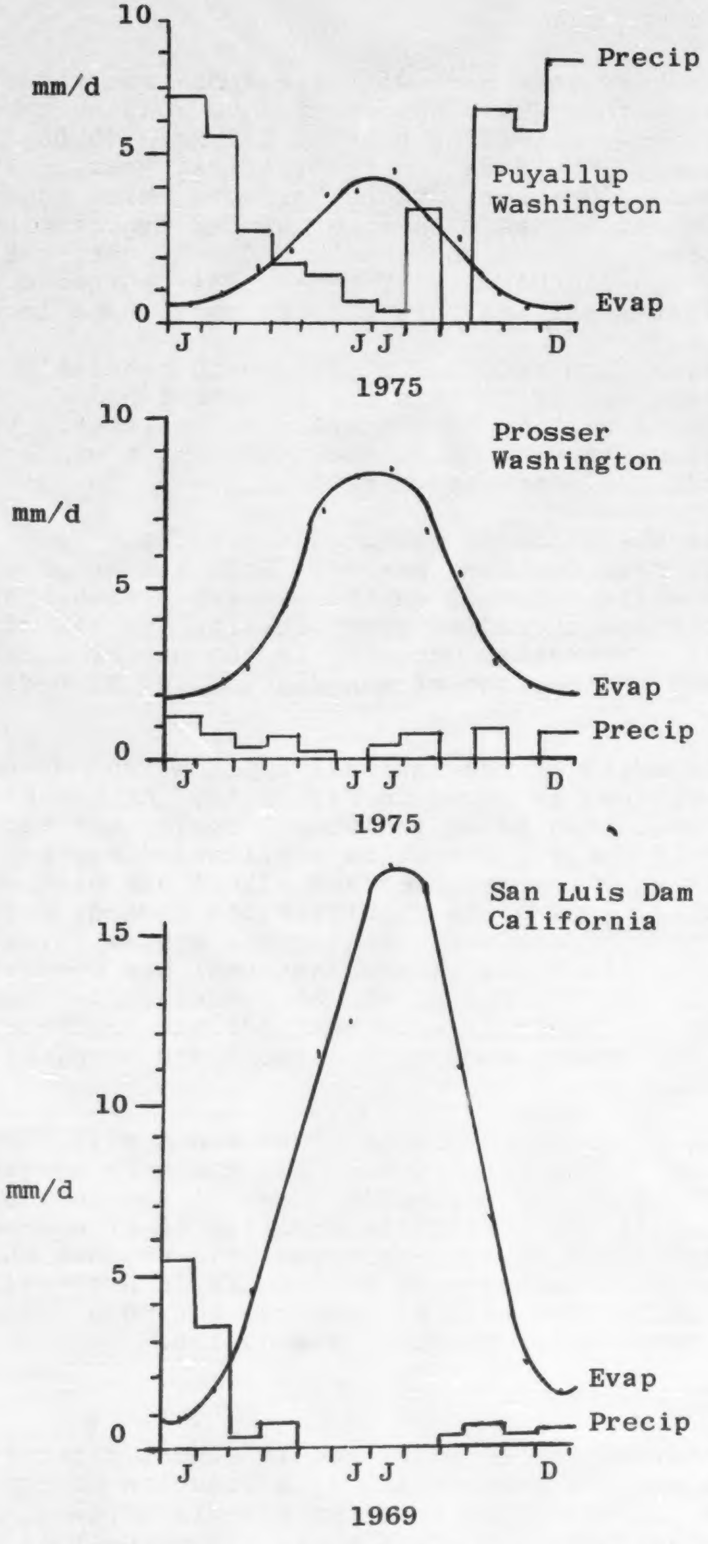


Figure 61. Precipitation-evaporation plots for western US locations

Yuma and Tucson have very high winter evaporation rates. They represent an area that would have a maximum loading rate for the U.S. For most years, a loading rate of 3.2 mm/d (0.08 gpd/ft^2) could be used. The data for the critical year of 1972 show an unusual storm in October. Tempe, Arizona which is in the same geographical area, has much lower winter evaporation rates and greater precipitation and thus would be a very marginal area for the use of non-discharging ET beds. This points out the importance of individual analysis for any particular location.

The winter evaporation rate in California is generally too small to allow for the use of ET beds for permanent homes. San Luis Dam in the central portion of the state has extremely high temperatures and evaporation rates in the summer, but winter precipitation exceeds the evaporation rate.

Two stations in the State of Washington are shown for contrast. Puyallup, near Seattle, has very high winter precipitation conditions while Prosser, on the eastern plains, has conditions of evaporation exceeding precipitation for all months. The available excess evaporation capacity in the winter months at Prosser is limited and the use of non-discharging ET beds would be marginal.

A generalized summary of the national applications of non-discharging ET bed systems is shown in Figure 62. Although each location should be evaluated on an individual basis, the map gives an indication of the regions where application may be feasible. The areas on the west coast and all of the eastern U.S. have weather conditions where precipitation exceeds evaporation during many months of the year, making the system infeasible. The southern intermountain region (cross-hatched) has conditions that may be favorable for the use of the ET concept. Another area, separating the two zones (single hatched) has conditions that are favorable for summer home applications and marginal for permanent home units.

It can be noted that the favorable areas are a significant part of the land area of the country but that the area contains only a small percentage of the unsewered homes of the nation. Another consideration in the overall feasibility of ET systems is that they are applicable in semi-arid and arid regions where water has a high value. Disposing of wastewater in a totally consumptive manner as is done with ET beds may not be a desirable alternative from a total water resource standpoint.

COST ANALYSIS FOR ET SYSTEMS

The cost of construction of an ET bed is almost directly proportional to its surface area, which is a function of the design loading rate. The loading rate for non-discharging, permanent home units constructed in areas where the concept is

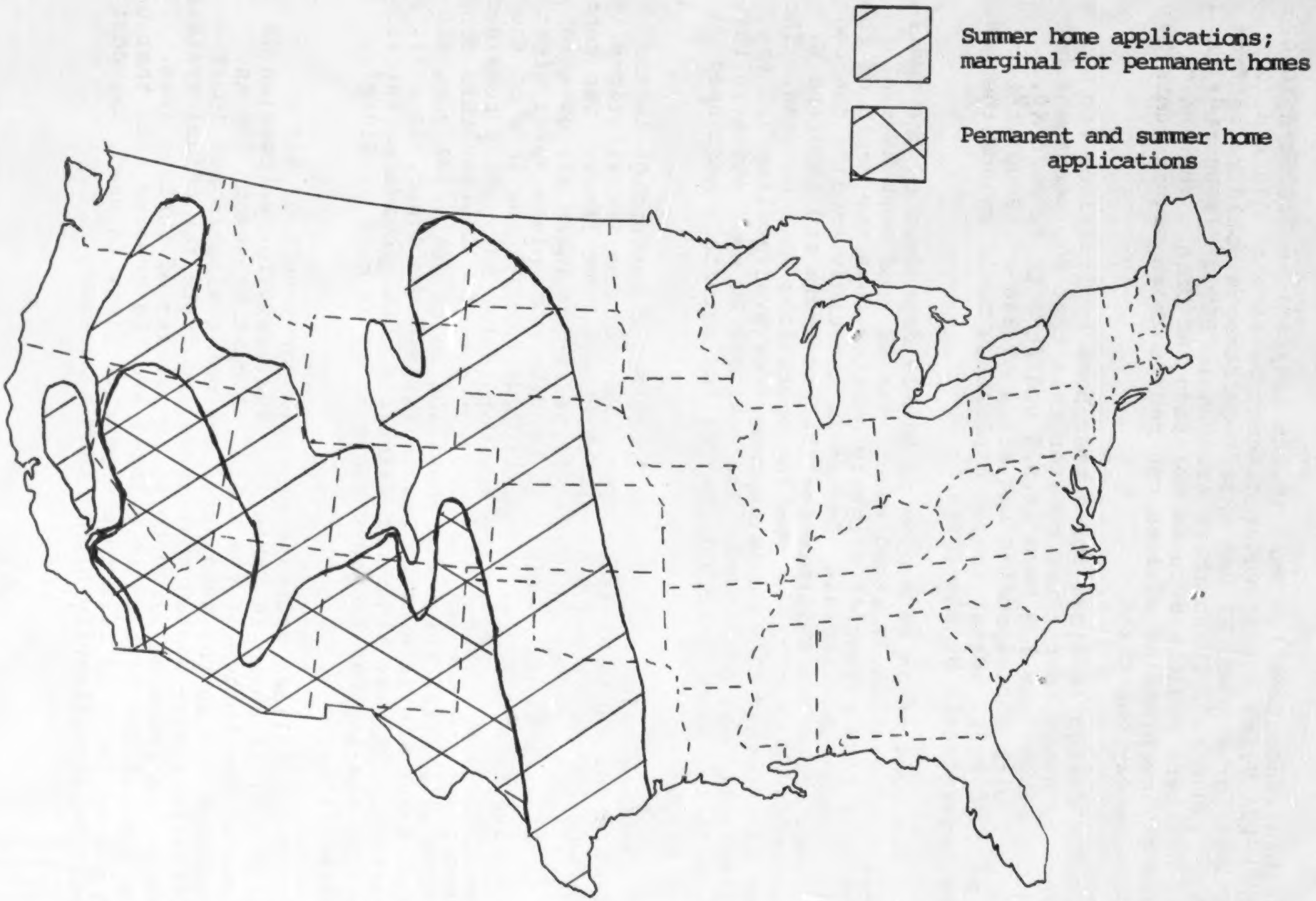

Summer home applications; marginal for permanent homes
Permanent and summer home applications

Figure 62. Areas of potential use of non-discharging ET beds in the U.S.

feasible range from 1.0 mm/d (0.025 gpd/ft^2) to 3.0 mm/d (0.075 gpd/ft^2). Using a wastewater generation rate of 850 ℓ/d (225 gal/day) for a home, ET bed size requirements would range from 280 m^2 (3000 ft^2) in southern Arizona to 840 m^2 (9000 ft^2) in more northern regions such as Colorado and Utah. The use of water saving plumbing devices can reduce these requirements by approximately one-third.

The design loadings for summer home applications are generally about four times greater than that for permanent homes and can range from 1.0 mm/d (0.025 gpd/ft^2) to 12 mm/d (0.3 gpd/ft^2) with corresponding bed sizes of 840 m^2 (9000 ft^2) to 70 m^2 (750 ft^3). Water saving appliances could reduce the bed area requirements by one-third.

The cost of an ET system is highly dependent on the availability of a suitably sized sand. The ET sand must have a capillary rise potential slightly greater than the depth of the bed. The earth materials removed in the excavation of the bed are very often not suitable for the bed media and imported ET sand obtained from gravel washing operations must be used. The cost of imported ET sand is dependent on availability and the distance it must be hauled. The cost for ET sand shown in this analysis is based on actual charges for materials purchased on this project.

Another major cost factor in ET bed construction is the type and thickness of liner used. Many of the installations in Colorado have utilized a 10 mil thickness, PVC liner. The cost is relatively low at \$0.37/m^2 (\$0.04/ft^2). There are questions as to whether it is possible to provide a complete water tight seal with this material that will last through the life of the bed. The liners used in the lysimeters for this study remained water tight for the two year project period. Whether this condition will exist for field installed units, especially at the point where the inlet pipe passes through the liner, is still a question. Thicker liners or materials that provide potentially tighter sealing can increase the cost by as much as \$10/m^2 (\$1.00/ft^2).

A generalized estimate of costs for a unit of 465 m^2 (5000 ft^2) is shown in Table 13. The basis for estimation is given at the bottom of the table. A cost breakdown for an installed bed in the study area was not available but local contractors have stated that installed costs for actual systems are in the range of \$1.00 to \$1.50 per ft^2 of surface area. If the cost of the ET sand in a local area is greater than that used in the estimate or if a more expensive liner is used, the cost could be significantly higher than that shown.

TABLE 13. TYPICAL COSTS FOR CONSTRUCTING ET SYSTEMS

Unit Costs

Item	Unit	Material & Equip.	Inst.	Total
1. ET sand, 20 miles haul and spread	yd^3	3.50[a]	$ 1.00[e]	$ 4.50
2. Plastic liner, 10 mil, PVC, 1 layer	ft^2	0.04[a]	0.04[e]	0.08
3. ET bed distribution Pipes, 4" diameter PVC	ft	0.50[c]	0.40[e]	0.90
4. Gravel, in place	yd^3	3.50[a]	1.00[e]	4.50
5. Excavation	yd^3	0.27[b]	0.38[b]	0.65
6. House drain pipe, 4" VCP inst.	ft	1.80[b]	2.20[b]	4.00
7. Septic tank, in place	ea	160[c]	120[c]	280

Estimate for Typical Bed
($5,000\ ft^2 \times 2$ ft deep)

Item	Unit Price	Quantity	Total
1. ET sand	$4.50/yd^3$	340	$ 530
2. Plastic liner	$0.08/ft^2$	5000	400
3. Distribution pipe	0.90/ft	625	560
4. Gravel	$4.50/yd^3$	38	170
5. Excavation	$0.65/yd^3$	375	260
6. House drain	4.00/ft	100	400
7. Septic tank	280 each	1	280
		Total Construction	$3,600
Engineering; permits; and contractor profit			~ 1,800[d]
		Total System Cost	$5,400
Unit cost to 5,000 ft^2 = $1.08/$ft^2$ ($11.60/$m^2$)			

[a] Actual charges for materials purchased on this project.

[b] Means Building Construction Cost Data, 34th Ed. (1976).

[c] Data from local contractor and local engineer.

[d] Data not available, value estimated.

[e] Based on estimated time for use of machine and operator or laborer, 105 HP dozer and op. @ $42/hr, labor @ $7/hr total.

MECHANICAL SYSTEM DESIGN

The sizing and costs of mechanical evaporation units are based on the relationships and equations developed in this study. No prototype units have been constructed. Further development of the concept could result in significant reductions in the size and cost requirements of a unit.

The design of a mechanical evaporation unit for operation under field ambient weather conditions requires the application of local climatological data to determine the rate of evaporation and an estimation of the number of days during which freezing will occur. When the wastewater flow rate exceeds the evaporation rate from the unit, storage facilities for the excess wastewater must be provided. When ambient air temperatures are below 4°C (40°F), the unit must be shut down and drained to the storage reservoir, allowing no evaporation to take place.

Two approaches can be used in calculating the approximate required size of a unit. These include: the use of the equations developed in the Results Section of this report, and the relationship between measured pan evaporation and actual evaporation that has been presented. One of the problems common to using the equations and reported data from the NOAA publication "Climatological Data" is the interpretation of wind speed measurements. It was shown in the experimental work that wind direction had a significant effect on the evaporation rate with the rotating disk evaporator (RDE). Weather bureau measurements of windspeed are made in the direction of the wind. By orienting the RDE in the direction of the prevailing wind, maximum evaporation rates can be attained. However, when using the mean monthly wind speed as reported in "Climatological Data", care must be exercised because of the height and conditions under which the wind speed was measured. The standard measurement height is 20 ft (6.1 m), however, this may vary and is reported with the data. The equations presented in the Theory Section of this report can be used to adjust the wind velocity to apply to the elevation of the disks.

Utilizing the weather data in Table 6 and the equation developed in the previous chapter for evaporation from the disks of the RDE, the values shown in Table 14 were calculated. Wind speed values were adjusted to an elevation of four ft (1.2 m) above the ground using the following equation:

$$W_4 = \left(\frac{4}{20}\right)^{1/7} W_{20} = 0.8\ W_{20}$$

The evaporation rate equation utilized was:

$$E_{(\ell/\mathrm{hr}\cdot\mathrm{m}^2)} = \left(0.0074 + 0.005\ W_{(\mathrm{kmph})}\right)\Delta H_{(\mathrm{gm/kg})} + 0.88\ R_S\ \frac{A_{vp}}{A_{ws}}$$

The second approach involves the correlation of disk evaporation rate with pan evaporation. It has been shown that:

$$E_{disk(\ell/hr.m^2)} = 0.42\ E_{pan(\ell/hr.m^2)}$$

The monthly evaporation rates for Boulder, Colorado are given in the table. A further consideration is that the unit cannot be operated when ambient temperatures are below 4°C (40°F). An analysis of the temperature data in Table 6 shows that the unit could be operated only a very small percentage of the time during the months of December, January and February when average temperatures are well below 4°C (40°F). During March and November the average temperature is near 4°C (40°F) and it has been assumed that the unit would operate fifty percent of the time. During the other months the unit is assumed to operate continuously. When these non-freezing utilization factors are applied to the evaporation data, the RDE evaporation rate values are obtained.

It can be noted that the values in Table 14 for RDE evaporation rate using the two methods are similar but not identical. The reason for this is that the term ΔH in the equation is highly sensitive to temperature and relative humidity variations. A change of only a few degrees in the monthly average temperature produces a marked change in the ΔH value. For this reason, the curve obtained must be considered as approximate. The curve in Figure 63 represents the calculated RDE evaporation values using the equation.

The maximum average loading rate for an RDE unit in Boulder is about 0.1 $\ell/hr.m^2$. This is the value from Figure 63 whereby the sum of the storage areas, indicated as ①, is equal to the excess evaporation area, indicated as ②. Operation of the unit would be terminated during January and February and the storage vault would be filling. During March the unit would operate about one-half time, and since the loading rate is greater than the evaporation rate, the vault would continue to fill slowly. Near the first of April, the vault would be full and from that point the evaporation rate would exceed the incoming wastewater flow rate, and the vault would begin to empty. Near the end of October the vault would be empty. Through November and December the vault would fill again and continue filling through the cycle to April.

The volume of vault storage required can be calculated from the inflow rate and the sum of the hatched areas designated by ①. For this case, the storage requirement is 100,000 liters (27,500 gal, 3500 ft^2). It is apparent that a large storage vault is required with this system in northern climates.

The required size of the RDE can be calculated from the yearly average loading rate of 0.1 $\ell/hr.m^2$. If a two meter

TABLE 14. CALCULATED EVAPORATION RATES $(\ell/\text{hr}\cdot\text{m}^2)$ FOR BOULDER, COLORADO

	Equation	Utilization Factor	RDE Evap.	Pan Correlation	Utilization Factor	RDE Evap.
January	0.027	0.0[a]	0.000	0.037	0.0[a]	0.000
February	0.058	0.0[a]	0.000	0.048	0.0[a]	0.000
March	0.086	0.5[b]	0.043	0.067	0.5[b]	0.033
April	0.123	1.0	0.123	0.090	1.0	0.090
May	0.167	1.0	0.167	0.121	1.0	0.121
June	0.165	1.0	0.165	0.174	1.0	0.174
July	0.196	1.0	0.196	0.161	1.0	0.161
August	0.184	1.0	0.184	0.140	1.0	0.140
September	0.153	1.0	0.153	0.078	1.0	0.078
October	0.124	1.0	0.124	0.065	1.0	0.065
November	0.072	0.5[b]	0.036	0.037	0.5[b]	0.019
December	0.063	0.0[a]	0.000	0.037	0.0[a]	0.000

[a] Assumes unit not operational during these months due to freezing conditions.

[b] Assumes unit operational 50% of the time due to intermittant freezing conditions.

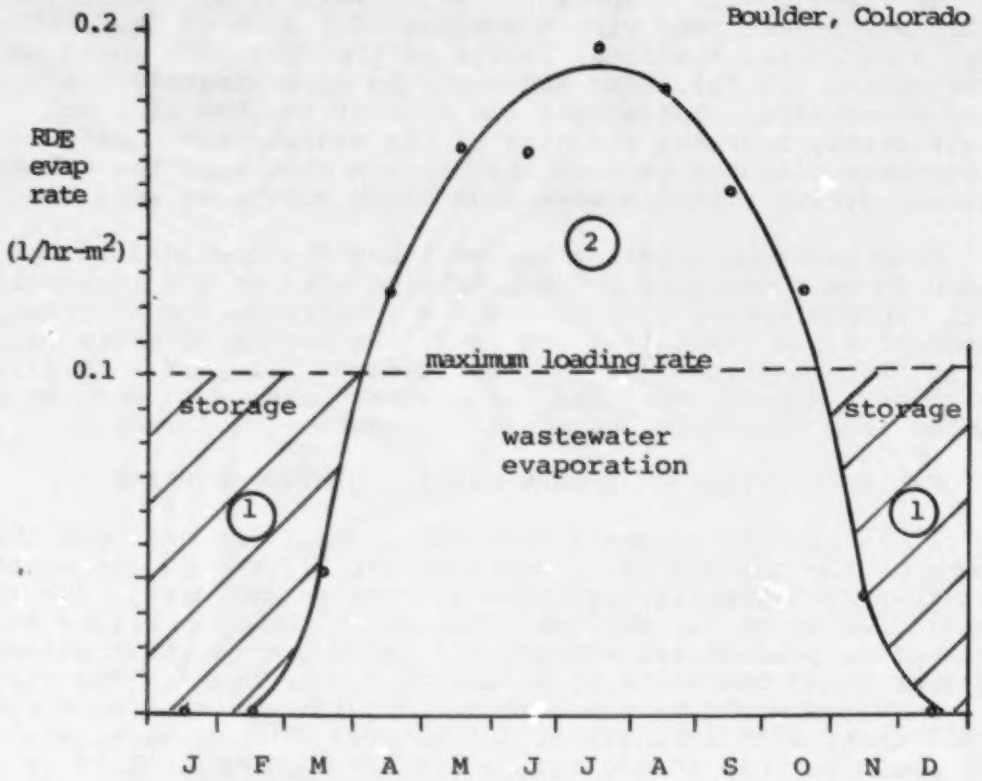


Figure 63. RDE loading rate curve considering evaporation potential and freezing weather periods for Boulder, Colorado.

(6.56 ft) diameter disk unit is used with a 0.71 submergence (fraction of the radius measured from the outside edge), an exposed area of 4.3 m^2 (46.3 ft^2) per disk is available. Using a wastewater flow rate of 850 liters per day, an average loading of 0.1 ℓ/hr·m^2 and 4.3 m^2/disk, a total of 83 disks would be required. A safety factor of 1.25 to 1.5 should be used to compensate for the uncertainties of the evaporation calculations and the variation in evaporation potential for different years. If 120 disks were used with a spacing of 2.5 cm (1 in.) between centers of disks, the total length of the disk pack would be three meters (10 ft). The RDE would be approximately the size of an automobile. Increasing the size of the RDE will not significantly decrease the size of the storage vault required in northern climates because the storage must hold the volume produced during slightly more than three months of cold weather.

Precipitation entering the unit was not included in the volume to be evaporated. The catchment area of the reservoir is small, approximately 2 m x 3 m = 6 m^2. With an annual precipitation of 0.5 m (19.6 in.) per year, the volume of water added due to precipitation is 3 m^3 (3000 liters) per year. This is less than one percent of the wastewater inflow rate and can be omitted from the calculation without appreciable error.

NATIONAL APPLICATION OF MECHANICAL EVAPORATION SYSTEMS

It is readily apparent that the size of the unit and the volume of the storage vault could be greatly reduced in southern climates where freezing problems are not encountered. The RDE evaporation curve for Hialeah, Florida is shown in Figure 64. No freezing periods are encountered in this area which allows for year round operation at a rate of 0.09 ℓ/hr·m^2. The size of unit required would be ten percent larger than that for Boulder, or 132 disks with a length of 3.3 meters. The storage requirement would be only 40,000 liters (10,600 gallons or 1500 ft^3). It can also be noted from the curve that in southern climates the use of a larger unit can reduce storage requirements. If a loading rate of 0.05 ℓ/hr·m^2 were used, the unit could keep up with wastewater flow in the winter and run intermittently in the summer. Under these conditions, no storage vat would be required. However, an RDE unit twice the size of the one designed for Boulder would be required for this condition. Similar design requirements would exist in all southern climates where freezing weather is not encountered.

For northern climates such as Canton, New York, the annual loading rate is approximately 0.05 ℓ/hr·m^2 as shown in Figure 65. This would require an RDE unit about twice the size of the one for Boulder, Colorado (2 m diameter x 3 m long). The storage requirement would be 130,000 liters (34,000 gal or 4600 ft^3).

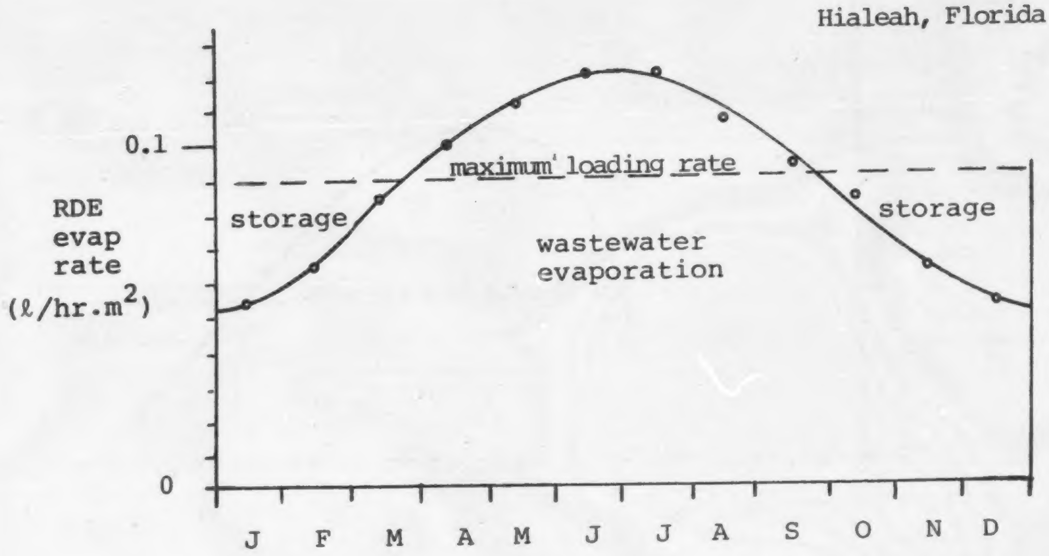


Figure 64. RDE loading rate curve considering evaporation potential for Hialeah, Florida.

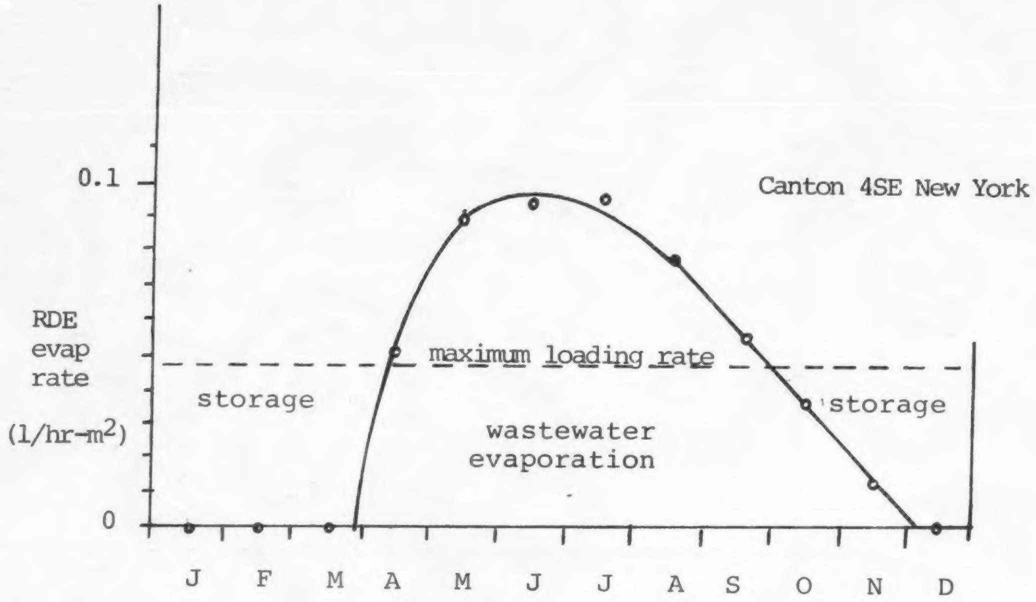


Figure 65. RDE loading curve considering evaporation potential and freezing weather periods for Canton, 4 SE, New York.

The RDE concept is applicable for permanent homes in any part of the U.S., except Alaska, but the vault storage volume will be very large in northern climates. The use of water saving devices can reduce the RDE and storage size by one-third. Summer home applications can be used throughout the U.S. Loading rates will be approximately fifty percent higher than for permanent homes (RDE about two-thirds size) and no storage volume will be required. In all cases, the RDE, with or without storage vault, must be preceded with a septic tank.

COST ANALYSIS FOR MECHANICAL EVAPORATION SYSTEMS

It is difficult to estimate the cost of a proposed mechanical system. The approach that was used was to scale up the actual costs of the model RDE used in the testing. Further development and optimization of the RDE concept and the use of mass production techniques could reduce unit costs significantly.

The cost of the rotating disk unit has been estimated with the option of two different disk materials, aluminum and plastic. A detailed cost listing is presented in Table 15. The fixed costs for a unit including assembly labor, motors, pumps, controls, drive shaft and other total to \$2700. The variable costs for different sized units include disk material at $\$1.53/\text{ft}^2$ ($\$16.46/\text{m}^2$) for aluminum or $\$0.68/\text{ft}^2$ ($\$7.32/\text{m}^2$) if plastic is to be used. The steel vat reservoir is estimated at $\$1.21/\text{ft}^2$ ($\$13.00/\text{m}^2$). When these values are combined the following equations result:

$$\text{Cost}_{(\text{Al})} = \$2700 + \$1.53/\text{ft}^2_{(\text{disk})} + \$1.21/\text{ft}^2_{(\text{vat})}$$

$$\text{Cost}_{(\text{plastic})} = \$2700 + \$0.68/\text{ft}^2_{(\text{disk})} + \$1.21/\text{ft}^2_{(\text{vat})}$$

The cost of the storage vault was based on the values in Table 16 and results in the expression:

$$\text{Cost}_{(\text{vault})} = \$300 + \$1.94/\text{ft}^3_{(\text{storage})}$$

These values are based on buried concrete vault storage. Less expensive means of storage might be desired to reduce this cost.

TABLE 16. VAULT STORAGE COSTS

	Unit	Unit Cost	
Excavation	yd^3	\$ 1.50	($\$1.96/\text{m}^3$)
Hauling	yd^3	1.50	($\$1.96/\text{m}^3$)
Concrete (complete)	yd^3	170.00	($\$221/\text{m}^3$)
Pumps and Controls	ea	300.00	
Total Storage	ft^3	1.94	($\$20.87/\text{m}^3$)

TABLE 15. COST ESTIMATES FOR ROTATING DISK EVAPORATOR

Item	Unit	Unit Cost $	Quantity	Total Cost $
ROTATING DISK UNIT				
Aluminum disks - 1/16" (includes material waste)	ft^2	1.36		
Disk fabrication (Al) @ $20/hr	ft^2	0.17		
Drive Unit -				
Bearings	ea.	8.00	8	64.00
Large pulleys	ea.	8.00	2	16.00
Sheaves	ea.	2.00	2	4.00
Belts	ea.	2.00	2	4.00
Motor w/speed control	ea.	225.00	1	225.00
Drive shaft	ea.	12.00	1	12.00
Shaft and motor supports (including fabrication)				240.00
Steel Tank -				
3/16" A36 plate	lb	0.26		
	ft^2	0.96		
Epoxy finish	ft^2	0.25		
Fabrication	hr	20.00	16	320.00
Controls	ea.	55.00	1	55.00
Unit fabrication	hr	20.00	24	480.00
Tank supports	ft	4.60	50	230.00
Concrete pad for unit	cu yd	100.00	1.9	190.00
Hauling to site				40.00
Electrician	hr	20.00	4	80.00
Installation	day	120.00	2	240.00
Design and inspection	ea.	500.00	1	500.00
Fixed Costs	unit		1	2700.00
Variable Disk Costs (Al)	ft^2	1.53		
Variable Tank Costs	ft^2	1.21		
Plastic Disk - 1/16" polypropylene (includes material waste)	ft^2	0.53		
Disk Fabrication (plastic) @ $20/hr	ft^2	0.15		
Variable Disk Costs (plastic)	ft^2	0.68		

Using the cost basis shown, the system cost for the examples cited are presented in Table 17. A value of $350 was added to include the cost of a septic tank complete and installed. The cost per 1000 gallons of wastewater disposed is presented, based on a 30 year unit life and 8.5 percent interest. The maintenance and operation costs were assumed to be very small and a figure of $25 per year was used.

It can be concluded that for the use of plastic disk RDE's with water saving devices for permanent homes in areas where freezing weather is not a problem, the system cost should be in the range of six thousand dollars. For more northern climates, the cost rises sharply and can exceed ten thousand dollars. Summer home installations, under the above conditions, should result in a system cost of approximately four thousand dollars. These costs are generally higher than those for a septic tank and leaching field. The RDE is a totally non-discharging system and in mild climate areas where subsurface discharge is not feasible, this system is probably cost competitive with many other alternatives.

The use of commercial heat in the form of a liquid or air heater to eliminate the need for the storage vault in cold weather applications is not feasible. The minimum heat required to evaporate the water under cold weather conditions is 600 calories per gram. It has been shown previously that the cost involved is approximately $100/1000 gallons. The use of a storage vault for winter conditions results in a cost well below this value.

CONCENTRIC CYLINDER EVAPORATOR

The concentric cylinder unit was devised to test the concept of evaporative disposal for the condition where a source of heated air was available, such as from a stack or chimney. The design of a unit of this type is specific to the conditions of the air that is available for use. The equations derived in the results chapter are specific for the geometry of the device tested and may not be directly applicable to a larger prototype unit, but the equations should provide an approximation of the performance of a larger unit.

The national applications of the CCE concept are very limited and relate to the specialized condition where a warm air source exists. Another application could be for winter conditions where air moving through the unit would be heated to provide continuous operation. It has been shown that the use of commercial heat to evaporate wastewater is a very costly operation and would be used only for very specialized conditions.

Another large drawback to the use of this concept from an economics standpoint is the very high cost of pumping air.

TABLE 17. RDE SYSTEM COSTS

	Total		$/1000 gal	
	Normal	Water Sav*	Normal	Water Sav*
Boulder, Colorado				
RDE aluminum	$ 8,721	$ 6,715		
storage & septic	7,440	4,960		
Total	$16,161	$11,675	18.16	13.12
RDE plastic	5,444	4,528		
storage & septic	7,440	4,960		
Total	$12,884	$ 9,488	14.48	11.76
Hialeah, Florida				
With storage				
RDE aluminum	9,325	7,115		
storage & septic	3,560	2,373		
Total	$12,885	$ 9,488	14.48	11.76
RDE plastic	5,718	4,712		
storage & septic	3,560	2,373		
Total	$ 9,278	$ 7,085	10.43	7.96
Without storage				
RDE aluminum				
Total	$14,742	$10,730	16.57	12.06
RDE plastic				
Total	$ 8,188	$ 6,356	9.2	7.14
Canton, New York				
RDE aluminum	14,742	10,730		
storage & septic	9,574	6,600		
Total	$24,316	$17,330	27.33	19.48
RDE plastic	8,188	6,356		
storage & septic	9,574	6,600		
Total	$17,762	$12,956	19.97	14.56
Summer Home - Boulder, Colorado				
RDE aluminum				
Total	$ 6,714	$ 5,376	30.60	24.51
RDE plastic				
Total	$ 4,530	$ 3,920	20.66	17.87

*Assumes 33 percent reduction in home water use with water saving devices.

Metcalf and Eddy, 1972, gives an expression for estimating the power requirement for pumping air as:

$$\mathrm{BHP} = \frac{W_a RT}{550\ ne_f}\left[\left(\frac{p_2}{p_1}\right)^n - 1\right]$$

where W_a = air flow rate (lb/s)

R = gas constant

T = temperature ^{o}K

n = compression constant, 0.283 for air

e = efficiency fraction

The minimum evaporation rate required for a CCU is 225 gal x 8.34 lb/gal x 1/24 x 60 x 60 = 0.022 lb/sec of water evaporated. If the piped air entering the compressor has a temperature of 20°C (68°F), an outlet pressure of 4 psig and an outlet humidity deficit ΔH = 10 lb/1000 lb, the air flow required would be 2.2 lb/sec. The horsepower required for 70 percent efficiency is:

$$\mathrm{BHP} = \frac{2.2 \times 53.5 \times 528}{550 \times 0.283 \times 0.70}\left[\left(\frac{18.7}{14.7}\right)^{0.283} - 1\right] = 40$$

or 30 kilowatts. Thirty kilowatt hours at $0.04 each will evaporate (0.022 x 3600)/7.5 = 10.5 gal of water, resulting in a cost of $120/1000 gal of water evaporated, an unacceptable cost for nearly all conceivable conditions.

It can be concluded that using commercial energy to enhance wastewater evaporation is very expensive. The rotating disk unit, which uses the heat and wind movement of ambient air, is a far more economic approach.

REFERENCES

Am. Soc. Civil Engrs. Tech. Committee. 1973, Consumptive Use of Water and Irrigation Water Requirements, M.E. Jensen, Ed., ASCE, New York, N.Y.

Bennett, E.R. and Linstedt, K.D. 1975, Individual Home Wastewater Characterization and Treatment. Completion Report Series No. 66, Environmental Resources Center CSU, Fort Collins, Colorado.

Bernhart, A.P., 1964. Wastewater Units for Individual Buildings and Homes. The Engineering Journal, Canada, 47, 7-19.

Bernhart, A.P. 1972. Small Wastewater Units for Soil Infiltration and Evapotranspiration. Notes of Presentation: Suburban Sewage Disposal Conference, Michigan Dept. of Health

Bernhart, A.P. 1973. Treatment and Disposal of Wastewater from Homes by Soil Infiltration and Evapotranspiration, University of Toronto, Press.

Bernhart, A.P. 1975. Return of Effluent Nutrients to the Natural Cycle through Evapotranspiration and Subsoil-Infiltration of Domestic Wastewater. Proceedings of the National Home Sewage Disposal Symposium Dec. 9, 10, 1975. American Society of Agricultural Engineers Publication Proc 175.

Bowen, I.S. 1926. The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface. Physical Rev. Ser. 2, 27, 779 - 787.

Bussinger, J.A. 1956. Some Remarks on Penman's Equations for the Evapotranspiration, Netherlands Journ. of Agr. Sci. 4, 77.

Cohen, S. and Wallman, H. 1974. Demonstration of Waste Flow Reduction from Households. Environmental Protection Technology Series, EPA - 670/2 - 74 - 071, US Environmental Protection Agency, Cincinnati, Ohio, September.

Dalinsky, J.S. 1971. The Sinusoidal Function of Regional Monthly Average Relative Pan Evaporation, Water Resources Research, 1, No. 3, 677-687.

REFERENCES

Duffy, J.A. and Beckman, W.A. 1974. Solar Energy Thermal Processes, New York: John Wiley and Sons.

Fitzgerald, D. 1886. Evaporation Trans. Am. Soc. Civ. Engrs. 15, 581 - 646.

Gray, Donald M. Ed. 1973. Handbook on the Principles of Hydrology, Water Information Center, Port Washington, New York.

Hasfurther, V.R., Foster, D.H., Lofgren, D.G., and Jenkins, S.J., 1975. Evapotranspiration as an Alternative for Second Home Waste Disposal Systems, Eisenhower Consertium Bulletin # 1, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Kohler, M.A., Nordenson, T.J. and Fox, W.E. 1955. Evaporation from Pans and Lakes, US Dept. of Comm. Weather Bureau Research Paper 38.

Lambe, W.T., 1951. Soil Testing for Engineers Wiley and Sons, N.Y., N.Y.

Ligman, K., Hutzler, N.H., and Boyle, W.C. 1973. Household Wastewater Characterization, submitted for Publication in Journal of the Sanitary Engineering Division ASCE,April.

Marciano, J.J. and Harbeck, G.E. 1954. Mass Transfer Studies US Geological Survey Professional Paper # 269.

Metcalf and Eddy Inc. 1972. Wastewater Engineering McGraw Hill Book Co., N.Y.

NOAA, Climatological Data, Published Monthly for each State by the National Oceanic and Atmospheric Administration.

Penman, H.L. 1948. Natural Evaporation from Open Water Bare Soil and Grass. Proc. Royal Soc. of London, A 193, 120-146.

Penman, H.L. 1956. Estimating Evaporation. Transactions of the American Geophysical Union, 37, 43 - 46.

REFERENCES

Rich, L.G. 1971. Unit Operations of Sanitary Engineering, John Wiley and Sons, Inc., New York, 1961. Reproduced by Linville Rich.

Rohwer, C. 1931. Evaporation from Free Water Surfaces, US Dept. of Agriculture, Technical Bulletin No. 271.

Standard Methods for the Examination of Water and Wastewater, 1976., 14th Edition, American Public Health Assoc., 1015 18th St., N.W. Washington, D.C. 20036.

Tanner, C.B. and Bouma, J. 1975. Evapo-Transpiration as a Means of Domestic Liquid Waste Disposal in Wisconsin. Small Scale Waste Management Project, Univ. of Wisc. Madison, Wisc.

US Census Bureau Report, 1970. US Government Printing Office, Washington, D.C.

Van Bavel, C.H.M. 1966. Potential Evaporation: The Combination Concept and its Experimental Verification. Water Resources Res. 2, 455 - 467.

Ward, J.C. 1977. Evaporation of Wastewater from Mountain Cabins, Environmental Resources Center Colorado State University, Fort Collins.

Wenk, V.D. 1971. Water Pollution: Domestic Wastes. A Technology Assessment Methodology, Vol. 6, Office of Science and Technology, PB - 202778-06, June.

Witt, M., Siegrist, R. and Boyle, W.C. 1975. Rural Household Wastewater Characterization. Proceedings of the National Home Sewage Disposal Symposium 1974. American Society of Agricultural Engineers, Proc. 175.

BIBLIOGRAPHY

Abbe, C. 1905. A First Report of the Relations Between Climates and Crops. Bulletin NO. 36, Weather Bureau, U.S. Department of Agriculture, Washington, D.C.

Alsholm, O., and Meurman, O. 1974. Systems Design and Computer Control of an Evaporation Plant. TAPPI, 57, 103

Anonymous. 1975. Evapotranspiration Possible New Sewage Treatment Process. Journal of Environmental Health, 37, 476

Anonymous. 1976. Guidelines for the Use of Total Evapotranspiration Systems. State of Washington, Office of Environmental Health Programs.

Baily, J., and Wallman, H.1971. A Survey of Household Waste Treatment Systems. Journal Water Poll. Control Fed. 43, 2349-2360

Bigelow, F.H. 1907. Studies of the Phenomena of Evaporation of Water over Lakes and Reservoirs. U.S. Monthly Weather Review 35, 311-316.

Black, T.A., Gardner, W.R. and Thurtell, G.W. 1969. The Prediction of Evaporation, Drainage and Soil Water Storage for a Bare Soil. Soil Sci. Soc. Am. Proc. 33, 655-660.

Blaney, H.F. and Criddle, W.D. 1950. Determining Water Requirements in Irrigation Areas from Climatological and Irrigation Data U.S.D.A-S.C.S T.P. 96, Washington, D.C.

Blaney, H.F., Rich, L.R., Criddle, W.D., et al. 1952. Consumptive Use of Water. Trans. ASCE, 117, 948-1020.

Blaney, H.F. and Criddle, W.D. 1962. Determining Consumptive Use and Irrigation Water Requirements. U.S. Dept. Agr. Tech. Bulletin 1275.

Blaney, H.F. and Morin, K.V. 1942. Evaporation and Consumptive Use of Water Formulae. Trans. Amer. Geophys. Union, 76-83.

Bond, J.S. and Willis, W.O. 1970. Soil Water Evaporation: First Stage Drying as Influenced by Surface Residue and Evaporation Potential. Soil Sci. Soc. Am. Proc. 34, 924-28.

Bibliography - cont'd

Bosen, J.F. 1960. A Formula for Approximation of Saturation Vapor Pressure over Water. Monthly Weather Review, Am. Meteorol. Soc. 95, 153-170.

Bowen, I.S. 1926. The Ratio of Heat Losses by Conduction and by Evaporation from Any Water Surface. Physical Review, Ser. 2, 27, 779-787.

Briggs, L.J. and Shantz, H.L. 1916. Hourly Transpiration Rate on Clear Days as Determined by Cyclic Environmental Factors, Jr. Agr. Res. 5 (I4).

Brady, D.K. 1970. Heat Dissipation at Power Plant Cooling Lakes Proc. Am. Power Conference 32, 528-36.

Brunt, D. 1952. Physical and Dynamical Meteorology, 2nd Ed., University Press, Cambridge.

Brutsaert, W. 1965. Evaluation of Some Practical Methods of Estimating Evapotranspiration in Arid Climates at Low Latitudes. Water Resources Res. 1, 187-191.

Caffery, R.P. and Ham, R.K. 1974. Role of Evaporation in Determining Leachate Production from Milled Refuse Landfills, Compost Science, 15, 11-15.

Calvert, J.D. and Heilman, W.L. 1973. Man Made Cooling Reservoir Performs as Expected. Power Engineering, 77, 40-43.

Cary, J.W. 1964. An Evaporation Experiment and Its Irreversible Thermodynamics. International Journal of Heat and Mass Transfer. 7, 531-38.

Cipolla, J.W. Jr., Lang, H., and Loyalka, S.K. 1974. Kinetic Theory of Condensation and Evaporation. J. Chem. Physics, 61, 69-77.

Christiansen, J.E., and Hargreaves, G.H. 1969. Irrigation Rerequirements from Evaporation. Trans. International Com. on Irrigation & Drainage, Vol.III, 23.569-23.596.

Christiansen, J.F. 1968. Pan Evaporation and Evapotranspiration from Climatic Data. Journal of the Irrig. and Drain. Div. Am. Soc. Civ. Engr., 94, 243-265.

Cummings, N.W. and Richardson, B. 1927. Evaporation from Lakes Physical Rev. 30, 527-534.

Bibliography - cont'd

Duffie, J.A., and Beckman, W.A. 1974. Solar Energy Thermal Processes. New York, John Wiley and Sons.

Dyer, A.J. 1961. Measurements of Evaporation and Heat Transfer in the Lower Atmosphere by an Automatic Eddy-Convection Technique. Quart. J. Roy, Meteorol. Soc. 87, 401-412.

Dyer, A.J. and Hicks, B.B. 1970. Flux-Gradient Relationships in the Constant Flux Layer. Quart. J. Roy, Meteorol. Soc. 98, 715-721.

Fritz, S. 1949. Solar Radiation on Cloudless Days. Heating & Vent. 4, 69-74.

Hamon, W.R. 1961. Estimating Potential Evapotranspiration. J. Hydr. Div. ASCE, 87 (HY3), 107-120.

Hanks, R.J., Gardner, H.R., and Fairbourn, M.L. 1967. Evaporation of Water from Soils as Influenced by Drying with Wind or Radiation. Soil Sci. Soc. Americ. Proc. 31,593-598.

Harbeck, G.E., Jr., Kohler, M.A. and Koberg, G.E. 1958. Water Loss Investigations: Lake Mead Studies. U.S. Geological Survey Professional Paper 268.

Jensen, M.E. and Haise, H.R. 1963. Estimating Evapotranspiration from Solar Radiation. Journal Irrig. and Drain. Div. Am Soc. Civ. Engr., 89, 15.

Keey, R.B. 1972. Drying Principles and Practice. Braunschweig: Pergamon Press.

Kennedy, R.E., and Kennedy, R.W. 1936. Evaporation Computed by the Energy Equation. Trans. Amer. Geophys. Union, 17,426-430

King, K.M. 1966. Mass Transfer-Profile Methods. Proc. Conf. Evapotranspiration, Am. Soc. Agric. Engr., 38-41.

Kohler, M.A., Nordenson, T.J. and Baker, D.R. 1959. Evaporation Maps for the United States. U.S. Dept. of Comm. Weather Bureau Technical Paper No. 37.

Kohler, M.A., Nordenson, T.J., and Fox, W.E. 1955. Evaporation from Pans and Lakes. U.S. Dept. Comm. W.B. Res. Paper 38.

Kohler, M.A., and Parmele, L.H. 1967. Generalized Estimates of Free-Water Evaporation. Water Resources Res. 3, (4), 997-1005.

Kuzmin, P.O. 1967. Hydrophysical Investigations of Landwaters. Int. Assoc. Sci. Hydrol. Int. Union of Geodesy and Geophys. 3, 468-478.

Lamoreux, W.W. 1962. Modern Evaporation Formula Adapted to Computer Use. Monthly Weather Rev., Am., Meteorol. Soc. 90, 26-28.

Lane, K.S. and Washburn, D.E. 1946. Capillarity Testing by Capillarimeter and by Soil Filled Tubes. Proc. Highway Research Board, Dec.

Lane, R.K. 1964. Estimating Evaporation from Insolation. J. Hydr. Div., ASCE, Paper No. 4025, 90, 33-41.

Lemon, E.R., Glaser, A.H., and Satterwhite, L.E. 1957. Some Aspects of the Relationship of Soil, Plant and Meteorological Factors to Evapotranspiration. Proc. Soil Sci. Soc. of Amer., 21 (5), 465-468.

Linacre, E.T. 1969. Climate and Evaporation from Crops. Closing Disc., J. Irrig. and Drain. Div., Am. Soc. Civ. Engr. 95, 348-352.

Lowry, R.L. and Johnson, A.F. 1942. Consumptive Use of Water for Agriculture. Trans. ASCE, 107, 1243-1256.

Makkink, G.F. 1957. Testing the Penman Formula by Means of Lysimeters. J. Inst. Water Engineering, 11 (3), 277-288.

McCuen, R.H. 1974. A Sensitivity and Error Analysis of Procedures Used for Estimating Evaporation. Water Resources Bulletin 10, 486-497.

Meyer, A.F. 1915. Computing Run-Off from Rainfall and Other Physical Data. Trans. ASCE, 79, 1056-1155.

Monteih, J.L., and Szeicz, G. 1961. The Radiation Balance of Bare Soil and Vegetation. Quart. Journal Roy. Met. Soc. 87, 159-170.

Monteih, J.L. 1965. Evaporation and Environment. Symp. Soc. Experimental Biology, 29, 205-234.

Mustonen, S.E., and McGuinness, J.L. 1968. Estimating Evapotranspiration in a Humid Region. U.S. Dept. Agr. Tech. Bull. No. 1389.

Bibliography - cont'd

Ostromecki. 1965. Remarks on Method of Computation of Water Requirements of Fields and Grasslands. Trans. from Polish U.S. Dept. of Int. T.T. 67-56052.

Polavarapu, R.J. 1970. A Comparative Study of Global and Net Radiation Measurements at Geulph, Ottawa and Toronto. J. Applied Met., 9, 809-814.

Richardson, B. 1931. Evaporation as a Function of Insolation. Trans. ASCE, 95, 996-1019.

Ritchie, J.T. 1971. Dryland Evaporative Flux in a Subhumid Climate: I. Micrometeorological Influences. Agr. J., 63, 51-55.

Shaw, R.H. 1956. A Comparison of Solar Radiation and Net Radiation. Bull. Am. Met. Soc. 37, 205-206.

Rose, C.W. 1968. Evaporation from Bare Soil Under High Radiation Conditions. Trans. 9th International Cong. Soil Sci.1,57-66.

Shjeflo, J.B. 1968. Evapotranspiration and the Water Budget of Prairie Potholes in North Dakota. U.S. Geological Survey, Professional Paper, 585-B.

Slessor, C.G.M., and Clelland, D. 1962. Surface Evaporation by Forced Convection: 1. Simultaneous Heat and Mass Transfer. Int. J. Heat Mass Transfer. 5, 735.

Stephens, J.C. 1965. Estimating Evaporation from Insolation. J. of the Hydraulics Div., ASCE, 91, 171-182.

Sutton, O.G. 1934. Wind Structure and Evaporation in a Turbulent Atmosphere. Proc. Roy. Soc. London, Series A, 146, 701-722.

Sutton, O.G. 1949. The Application of Micrometeorology of the Theory of Turbulent Flow Over Rough Surfaces. Quart. J. Roy. Meteorol. Soc., 75, 335-350.

Tanner, C.B. 1960. Energy Balance Approach to Evapotranspiration from Crops. Proc. Soil Sci. Soc. of Amer., 24, (1).

Tanner, C.B. and Bouma, J. 1975. Evapotranspiration as a Means of Domestic Liquid Waste Disposal in Wisconsin. Small Scale Waste Management Project, Univ. of Wisc., Madison, Wisc.

Tanner, C.B. and Pelton, W.L. 1960. Potential Evapotranspiration Estimates by the Approximate Energy-Balance Method of Penman J. Geophys. Res., 65, 3391-3413.

Bibliography - cont'd

Tanner, C.B. 1968. Evaporation of Water from Plants and Soils. In: Water Deficits and Plant Growth. T.T. Kozloski (Ed.) Vol. I. New York: Academic Press.

Thompson, J.R. 1974. Energy Budget Measurements over Three Cover Types in Eastern Arizona. Water Sesources Research Vol.10,5.

Thornthwaite, C.W., and Holzman, B. 1939. The Determination of Evaporation from Land and Water Surfaces. Monthly Weather Rev., 67, 4-11.

Thornthwaite, C.W. 1948. An Approach Toward a Rational Classification of Climate. Geograph. Rev., 38, 55.

U.S. Dept. of Interior. 1954. Water Loss Investigations: Vol. 1 Lake Hefner Studies Tech. Report. Geol. Surv. Prof. Paper 269, Wash., D.C.

van Bavel, C.H.M. 1966. Potential Evaporation: The Combination Concept and its Experimental Verification. Water Resources Res., 2 (3), 455-467.

Wallace, A.T. and Sturm, G.L. 1975. The Applicability of Evapotranspiration Systems for On-Site Wastewater Disposal in Idaho. Final Report of the Idaho Research Foundation, Inc.

Wartena, L. 1974. Basic Difficulties in Predicting Evaporation. J. Hydrology, 23, 157-177.

Weinberg, B., and Kreith, F. 1974. Evaporation by Convection from a Plate With Finite Sources. 5th International Heat Transfer Conference, Tokyo, Japan.

Wesely, M.L., and Thurtell, G.W. and Tanner, C.B. 1970. Eddy Correlation Measurements of Sensible Heat Flux Near the Earth's Surface. J. Applied Meteorology, 9, 45-50.

Whiting, D.M. 1975. Use of Climatic Data in Design of Soils Treatment Systems. EPA-660/2-75-018.

Williams, G.P. 1961. Evaporation from Water, Snow and Ice. Proceedings of Hydrology Symposium No. 2-Evaporation, Queen's Printer, Ottawa.

Wright, J.L., and Jensen, M.E. 1972. Peak Water Requirements of Crops in So. Idaho. J. Irrig. and Drain. Div., ASCE 98 (IR2), 193-201.

Bibliography - cont'd

Yamaoka, Yoshita. 1958. Experimental Studies on the Relation Between Transpiration Data and Meteorological Elements. Trans. of Amer. Geophys. Union, 39 (2).

Young, A.A. 1947. Evaporation from Water Surfaces in California. U.S. Dept. of Agriculture, SCS Bulletin, No. 54.